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DETERMINATION OF THE RATIO OF L-X-RAYS TO ALPHA PARTICLES EMITTED BY PU-239

TECHNICAL REPORT NO. AFWL-TR-69-82

July 1969

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico

102

AFWL-TR-69-82

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Captain USAF

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FOREWORD

The research described was performed under Program Element 6.24.05.06.F, Project 1831, Task 1831.10, and was previously reported by the author in a thesis (GSP/PH/68-3) of the same title, presented to the faculty of the Air Force Institute of Technology in partial fulfillment of requirements for the Master of Science degree.

Inclusive dates of research were July 1967 through December 1967. The report was submitted 23 June 1969 by the AFWL Project Officer, Captain Neil A. Coddington (WLBN).

Information in this report is embargoed under the U.S. Export Control Act of 1949, administered by the Department of Commerce. This report may be released by departments or agencies of the U.S. Government to departments or agencies of foreign governments with which the United States has defense treaty commitments, subject to approval of AFWL (WLBN).

The author thanks Captain James Morrow, Mr. Edward Clements, Lt Paul Zielie, MSgt George H. Lake, MSgt Olie B. Graves, SSgt Frank Aguilar, and especially Mr. Harry M. Murphy, whose computer programs made the analyses of data considerably easier.

This report has been reviewed and is approved.

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ABSTRACT

(Distribution Limitation Statement No. 2)

A method of absolute counting was used to determine a value of 0.0459 $\pm$ 0.0014 for the ratio of L-X-rays to alpha particles emitted by Pu-239. The relative intensities observed for the $L_\alpha/L_\beta/L_\gamma$ X-ray groups were 1.00/1.23/0.27 respectively and a value of 3.04 $\pm$ 0.57 x 10^{-4} was obtained for the ratio of 51.56-kev gamma rays to alpha particles emitted by Pu-239. The emission rates of alpha particles were measured with a detector made of lithium-drifted silicon, operated at room temperature and at a pressure of 0.001-torr. The emission rates of photons were measured with a detector made of lithium-drifted germanium (Ge(Li)), cooled to a temperature of 77°K. All measurements were recorded with a 400-channel pulse-height analyzer. The efficiency of the Ge(Li) detector for photoelectric interactions was established from a series of measurements of a source of Am-241 with a known activity. The geometric arrangements of the sources and the detectors were varied widely to avoid biased results that may have accrued if all measurements had been made with the geometry fixed. The count rates recorded by the detection apparatus were corrected for the efficiency of the detector and the geometry of the measurement by means of a computer program, to yield the rate of emission of the source for each energy of interest.

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CONTENTS

CONTENTS (cont'd)

ILLUSTRATIONS

TABLES

EQUIPMENT

Model No.	Nomenclature	Manufacturer
TE-3-6	Ge(Li) Detector	TMC*
50-110-1/2A	Si(Li) Detector	TMC
336	FET Preamplifier	TMC
339	Power Supply/Bin	TMC
341	Linear Pulse Amplifier	TMC
344	Pulse Output Shaper	TMC
353	Detector Bias Supply	TMC
401D	Pulse Height Analyzer	TMC
109	FET Preamplifier	ORTEC**
410	Multimode Amplifier	ORTEC
806	Detector Cooler	ORTEC
C-22	Cryostat	Linde
865C	Power Supply	Harrison
PS-101	Power Supply	Simtec Ltd.

* Technical Measurements Corporation

** Oak Ridge Technical Enterprises Corporation

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SECTION I

INTRODUCTION

The experiment described herein was undertaken to determine accurately the ratio of L-X-rays to alpha particles emitted by Pu-239. This information is required by the Air Force to enable the quantitative definition of a plutonium alpha-hazard to be made from the results of an L-X-ray survey of an area suspected to be contaminated with plutonium.

The reference in this report to plutonium L-X-rays is in accord with general practice, although the designation is incorrect. These X-rays actually arise from the de-excitation of the daughter nucleus, U-235, following an internal conversion process.

The process of interest to this study is associated with the decay of Pu-239 to U-235 by emission of alpha particles. In 10.7 percent of the decays, Pu-239 emits an alpha particle with energy of 5.096 Mev (Ref. 1:818) to produce an excited state in U-235. This state is 51.67 kev above the ground state and has sufficient energy to convert L-electrons, which have binding energies between 17 and 23 kev. This results in the production of L-X-rays with energies between 12 and 23 kev, or in Auger processes which yield radiations with energies that are minute, and therefore of negligible concern to this study.

1. PRIOR MEASUREMENTS OF L-X-RAYS

Soft radiations from Pu-239 were first detected by Ghiorso in 1944. The first measurements made to compare emission rates of alpha particles and photons were reported by West and Dawson (Ref. 2) and West, Dawson, and Mandleberg (Ref. 3) in 1951. They used a proportional counter filled with krypton and methane and a 30-channel pulse-height analyzer to obtain a value of 0.04 $\pm$ 0.01 for the ratio of L-X-rays to alpha particles emitted by Pu-239, and relative intensities of 1.0/1.8/0.3 for the L-X-ray groups L_α, L_β, L_γ. H. Israel (Ref. 4) made a similar determination in 1952 with a proportional counter filled with argon and methane and a single-channel pulse-height analyzer. He reported 0.029 $\pm$ 0.0145 L-X-rays per alpha particle emitted by Pu-239, with relative intensities of 1.0.1.4/0.3 for the $L_\alpha/L_\beta/L_\gamma$ X-ray groups. In 1967, Swinth (Ref. 5:284) reported 0.0485 $\pm$ 0.0004 L-X-rays per alpha particle from Pu-239, by counting photons in coincidence with alpha particles. Swinth used a proportional counter filled with argon and methane to count alpha particles and a scintillation crystal made of sodium iodide to detect the L-X-ray photons.

2. INSTRUMENTS FOR MEASURING L-X-RAYS

Several portable instruments (Refs. 6 and 7) have been developed for performing field measurements of plutonium L-X-rays to assist in delineating the boundaries of areas contaminated with material which emits alpha particles. Potentially, such instruments should be of great assistance in speeding initial surveys and providing as good or better accuracy than the instruments for surveying alpha particles, because the low-energy photons are less susceptible than alpha particles to absorption in thin overburdens of material. Although the technology of such instruments is advancing rapidly, it has not yet advanced sufficiently to warrant confidence in their effectiveness, except under ideal conditions. All such instruments rely in part on mechanical discrimination of photon energies through the use of very thin (~2-mm thick) sodium iodide scintillation detection elements that are very fragile as a consequence. Their thinness minimizes their response to photons with high-energies (greater than about 80 kev). A single-channel analyzer is used in some of the instruments to provide additional discrimination of energies by electronic means.

Some of the shortcomings of the instruments that remain to be overcome by further technical development are operational characteristics that are dependent on temperature stability, drift of calibration settings with time, and spurious counting caused by dark-current noise in photomultiplier tubes.

Some of the problems associated with the detection of L-X-rays which remain to be investigated further before such instruments can be deployed most effectively include (1) uncertainty in the ratio of L-X-rays to alpha particles; (2) background counting rates that vary with geography because of radioactive mineral deposits; (3) variations in the response of the instrument as a function of the geometry of the source and the detector; (4) difficulties in preparing calibration sources to be used to establish the baseline performance of detection instruments for both alpha particles and L-X-rays; and (5) potential methods for evaluating the magnitude of and correcting for the attenuation of photons in overburdens of soil, moisture, etc. Schmidt (Ref. 7) has done a considerable amount of work on problems (2) and (3), above.

SECTION II

DESCRIPTION OF EXPERIMENTAL EQUIPMENT

The equipment used in this experiment falls into six divisions of components or categories: (1) the pulse-height analyzer used to record the spectra of both photons and alpha particles, (2) the pulse shaper used to condition the output pulses of the linear amplifiers for storage by the pulse-height analyzer, (3) the photon detection system, including all components from the detector through the linear amplifier, (4) the alpha detection system, including all components from the detector through the linear amplifier, (5) the sources of plutonium (Pu-239), and (6) the sources of americium (Am-241). Each of the categories is discussed in some detail in the paragraphs which follow.

1. PULSE-HEIGHT ANALYZER (PHA)

The pulse-height distributions produced by both photons and alpha particles were obtained with a 400-channel analyzer manufactured by Technical Measurements Corporation (TMC Model 401D). Numerous tests, similar to those described by Crouch and Heath (Ref. 8) were conducted to determine the operating characteristics of the PHA.

a. Live-Timer Accuracy

The live-timer in the PHA was calibrated with an Ortec (Model 204) pulse generator. The live-time for storage of pulses of various amplitudes, as indicated by the PHA, was compared with the live-time which had actually elapsed. The elapsed live-time was calculated from the number of pulses stored and the known frequency of the pulser. The internal "clock" oscillator of the PHA was adjusted to bring its indication of live-time within 0.25 percent of that actually elapsed.

b. Live-Timer Precision

Errors in the live-timer can degrade counting precision when a low-level source is counted in the presence of a high-background count rate. The degradation in precision of the PHA was determined by comparing the mean value for a series of measurements (made with a scintillation detector) of a 2443-cpm (Zn-65) source counted alone with the mean value of a series of measurements of the same source counted along with a 22,500-cpm (Cs-137) source. The comparison was based on two sets of measurements, which consisted of four 10-minute counts of the Zn-65 alone and in the presence of the Cs-137.

The mean value of the count rate under the photopeak when the Zn-65 was counted alone was 8.7 cpm higher than the corresponding value for the Zn-65 counted in the presence of the Cs-137. This difference was within the standard error (11.0 cpm) of the difference in mean values of the two sets of count-rate measurements. The precision of the live-timer was therefore considered to be satisfactory because the difference observed was not significant, statistically, according to the method shown in Reference 9.

c. Integral Linearity

A pulser was used to obtain 53 measurements of pulse-height versus thresholds of the PHA storage channels. The results were least-squares fit to a first order polynomial equation, and showed a zero intercept with a mean deviation from linearity of less than 0.2 percent.

d. Differential Linearity

A qualitative check of the differential linearity of the PHA was performed (the results were not subjected to a detailed analysis). A sliding pulse generator (Berkeley Nuclear Corporation, Model GL-3) was used to generate pulses with amplitude that increased linearly with time. The pulse repetition rate was gradually increased to determine the maximum rate of pulse storage for the PHA. The differential linearity was observably uniform, but as the repetition rate was increased above 6500 pps, jump discontinuities appeared in the otherwise linear pulse-height spectrum, at which point the PHA was considered to have failed the test. During later experiments, the count rates were limited to less than 1000 cps to ensure that the data of interest would not be affected by breakdown in the differential linearity.

2. PULSE SHAPER

The output pulses of the amplifiers for the detection systems of both photons and alpha particles were modified with a pulse shaper (TMC Model 344) to improve the response of the PHA. The normal pulse output of either amplifier has a gaussian shape. The gradual change in slope of the pulse in its rise toward maximum amplitude leads to uncertainty (for the analog-to-digital converter in the PHA) in the precise location of the maximum and may result in PHA storage errors. The pulse shaper modifies the approach to maximum into a triangular shaped pulse, with a moderate slope and a rapid change in direction of slope at maximum amplitude, similar to the shape recommended by Fairstein (Ref. 10:53).

3. PHOTON DETECTION SYSTEM

The physical arrangement of the system used to detect the low-energy photons is shown in Figure 1. A block diagram of the system in Figure 2 shows how the components are interconnected and their model numbers. Pertinent operating characteristics of each component are discussed in the paragraphs which follow.

a. Detector

A detector (TMC Model TE-3-6) made of lithium-drifted germanium (GE(Li)) was used during the course of this experiment. The detector has an area of 3 cm^2, and an active depth of 6 mm with an unusally thin "dead" layer (inactive surface region) of less than 3-microns thickness. A molecular sieve was used to maintain the detector at a pressure of 0.0001-torr. Thermal noise was minimized by coupling the detector to a 25-liter cryostat containing liquid nitrogen (77°K). The housing for the detector was constructed of aluminum, 0.125-inch thick, with a 0.010-inch beryllium window provided to minimize the attenuation of low energy photons.

b. Preamplifier

The preamplifier (TMC Model 336) was operated at room temperature with a thermal noise level of less than 2.5-kev FWHM (full-width at half the maximum amplitude of a monoenergetic pulse input). The charge-sensitive input stage, consisting of a field-effect transistor, is coupled capacitively to the detector with a lead length of about one inch.

c. Main Amplifier

The linear pulse amplifier (TMC Model 341) is equipped to provide unipolar or bipolar outputs. A switch is provided to select either delay-line or differentiation and/or integration time-constants of 0.1 to 10 microseconds. The gain is continuously adjustable from 1 to 1300. The unipolar output mode was used during this experiment with time-constants of two microseconds selected for differentiation and integration. The selection of time-constants was based on the best system resolution of the 60-kev gamma ray photopeak of Am-241.

d. Bias Supply

The bias supply (TMC Model 353) for the detector provided regulated voltages from 0 to 990 volts in steps of 10 volts with less than 500 microvolts

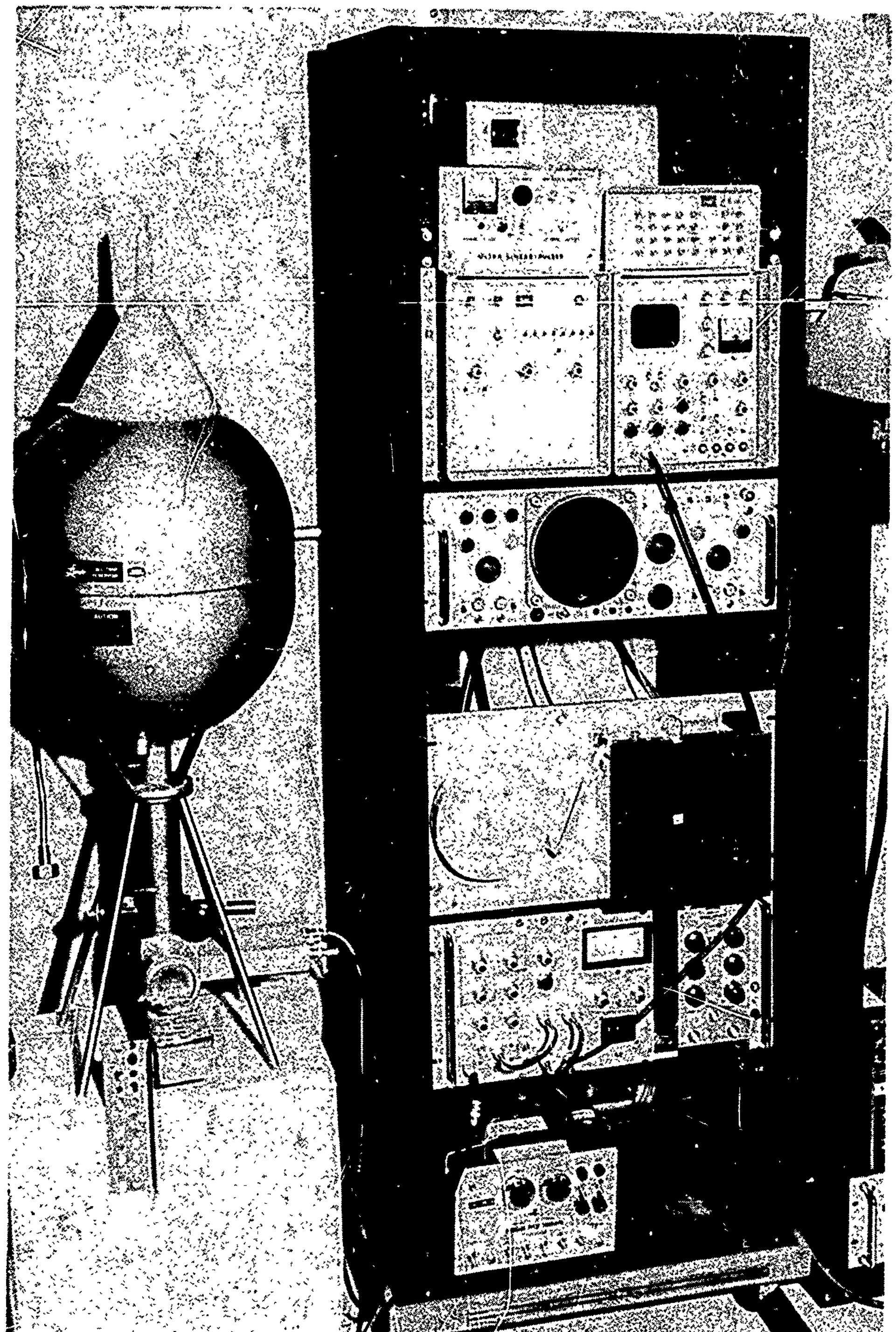
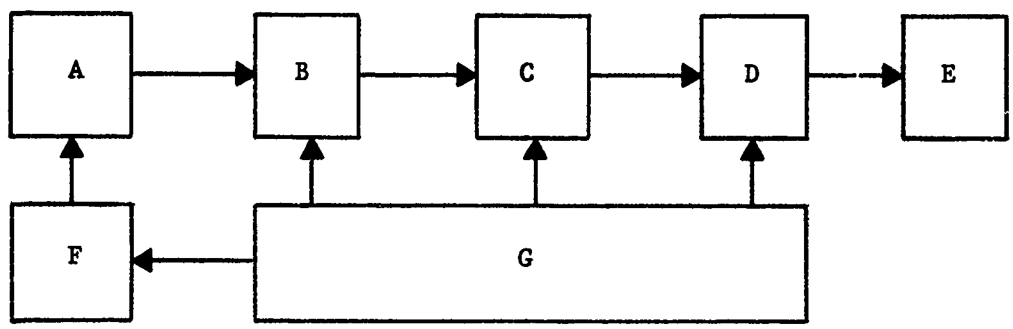


Figure 1. Photon Detection System



A - TE-3-6 Ge(Li) Detector

B - Model 336 Preamplifier

C - Model 341 Linear Amplifier

D - Model 344 Pulse Output Shaper

E - Model 401D Pulse Height Analyzer

F - Model 353 Detector Bias Supply

G - Model 339 Bin/Power Supply

Figure 2. Block Diagram of Photon Detection System

of ripple. The Ge(Li) detector was operated at 990 volts bias and drew less than 0.05 nanoamperes of current.

e. Power Supply/Bin

All components except the detector and preamplifier were mounted in a modular system bin (TMC Model 339), and all were powered by the built-in power supply, designed by Power Designs, Pacific. The power supply provided positive and negative voltages of 12 and 24 volts that were well regulated.

4. ALPHA DETECTION SYSTEM

A block diagram of the system used to detect alpha particles is presented in Figure 3. This shows the model numbers of the components of the system and how they are interconnected. The characteristics of each component are discussed in detail in the following paragraphs.

a. Detector

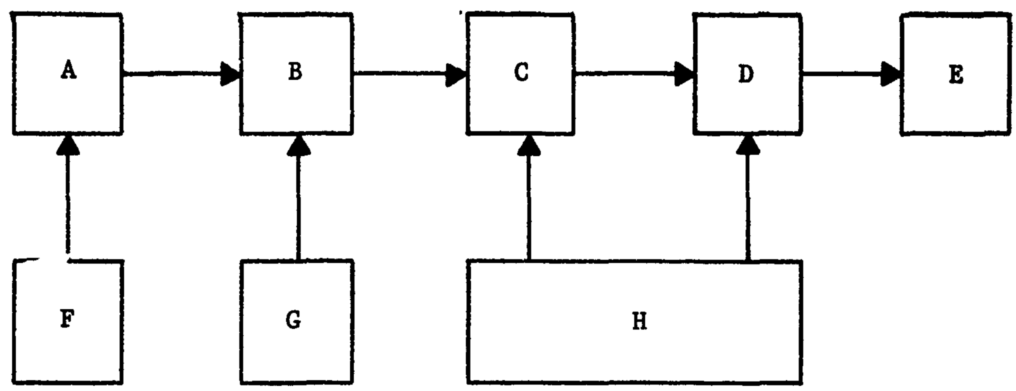
The detector used to count alpha particles (TMC Model 50-110-1/2A) was made of lithium-drifted silicon (Si(Li)) with a sensitive depth of 0.5 mm and an active area of 110 mm^2. It was operated at room temperature to degrade the resolution so that the ionization peaks in the pulse-height spectra were spread over several channels of the PHA. This eliminated the need for a biased amplifier with its associated drift in gain by providing a sufficient number of data points in each peak for an adequate statistical analysis.

b. Vacuum Chamber

The vacuum chamber was designed by Ortec (Model 806) for counting of charged particles. The chamber has necessary fittings to permit cooling of the detector by controlled expansion of gaseous CO_2, and has internal stand for mounting sources between 0 and 4.42 inches from the detector. The disassembled chamber with a source-mounting platform, designed and constructed at AFWL, is shown in Figure 4.

c. Preamplifier

The input stage of the charge-sensitive preamplifier (Ortec Model 109), coupled capacitively to the detector, consists of a field-effect transistor with a large input impedance. A choice of X1 or X10 gain settings is available and the preamplifier is provided with an internal bias resistance network (1000 megohn) for operation at low temperatures. For this experiment, an external bias network of 6.11 megohms resistance was used to operate the detector at room temperature.



A - 50-110-1/2A Si(Li) Detector

B - Model 109 Preamplifier

C - Model 410 Multimode Amplifier

D - Model 344 Pulse Output Shaper

E - Model 401D Pulse Height Analyzer

F - Model 865C Power Supply

G - PS-101 Power Supply

H - Model 339 Bin/Power Supply

Figure 3. Block Diagram of Alpha Detection System

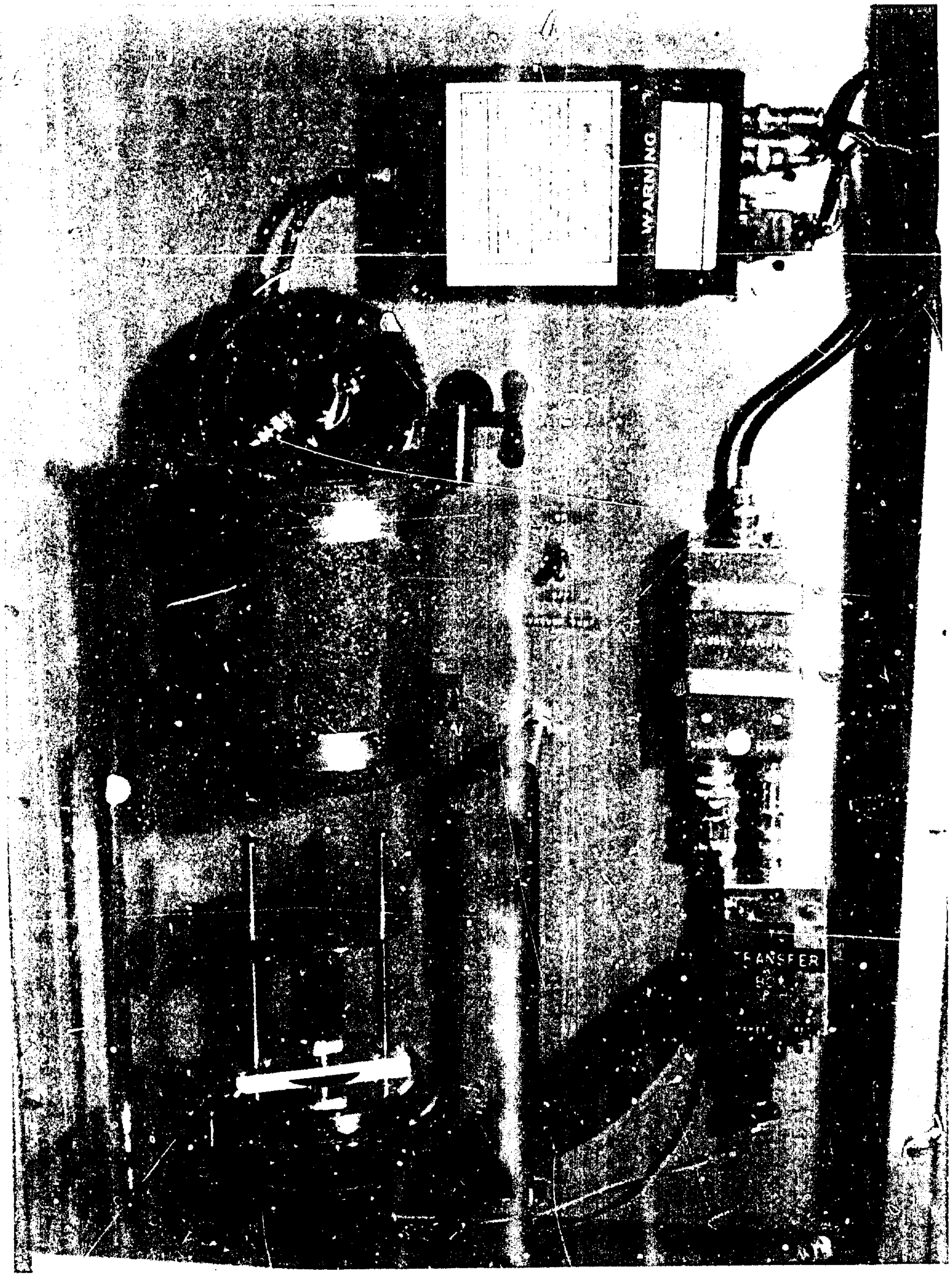


Figure 6. Disassembled Vacuum Chamber, Source Positioning Mechanism, Alpha Detector, and Preamplifier

d. Main Amplifier

The main amplifier, manufactured by Ortec (Model 410) has features similar to those described for the TMC amplifier, used as part of the photon detection system. Time constants of 1 microsecond were used for single differentiation and integration during this experiment because they were found to provide a restoration of the baseline between pulses nearest to zero volts.

5. PLUTONIUM SOURCES

The two sources shown in Figure 5 were obtained from the Eberline Instrument Corporation for this experiment. The isotopic percentages (determined by mass spectrographic measurements when the source material was removed from the reactor on 31 October 1965) supplied by the manufacturer in units of atom percent were Pu-239, 99.233 $\pm$ 0.019; Pu-240, 0.752 $\pm$ 0.015; and Pu-241, 0.015 $\pm$ 0.011. The activities of the two sources P-5611 and P-5612, were 10.2 μCi (0.50 $\pm$ 0.03 μCi/cm^2) and 15.8 μCi (0.78 $\pm$ 0.03 μCi/cm^2) respectively, as reported by the manu- from measurements made in 2-pi geometry with a gas-flow proportional counter (Ref. 11).

The sources were prepared by electroplating the plutonium on 2-inch-diameter nickel disks, followed by a heat treatment in open flame to minimize losses or contamination because of handling. The heat treatment (Ref. 11) resulted in the formation of a layer of oxide over the surface of the source and/or a stronger bond between the plutonium plate and the nickel base metal.

6. AMERICIUM SOURCES (AM-241)

Two americium sources were used throughout this experiment. The Am-241 source used to calibrate the photon detection system for energy and efficiency was one of a set of calibrated reference sources (shown in Figure 6) obtained from the International Atomic Energy Agency (IAEA). The activity of the IAEA Am-241 source was certified to be 10.94 $\pm$ 0.036 μCi on 1 January 1967. This point source ($\sim$1 mm dia.) was centered on a thin Mylar disk, which was supported by an aluminum ring that was 3 cm in diameter. The Am-241 was firmly fixed to the Mylar with a coating of lacquer or epoxy, which limited its use to photon calibration.

The source (S-307) used to correlate the counting measurements of the alpha particle and photon detection systems consisted of a 1.5-mm^2 plating of Am-241 on a platinum foil that was 1.0 cm in diameter. This source was listed in the AFWL source inventory as having an activity of 0.180 μCi (398,500 dpm).

Figure 5. Plutonium Disk Source Set, P-5611 and P-5612

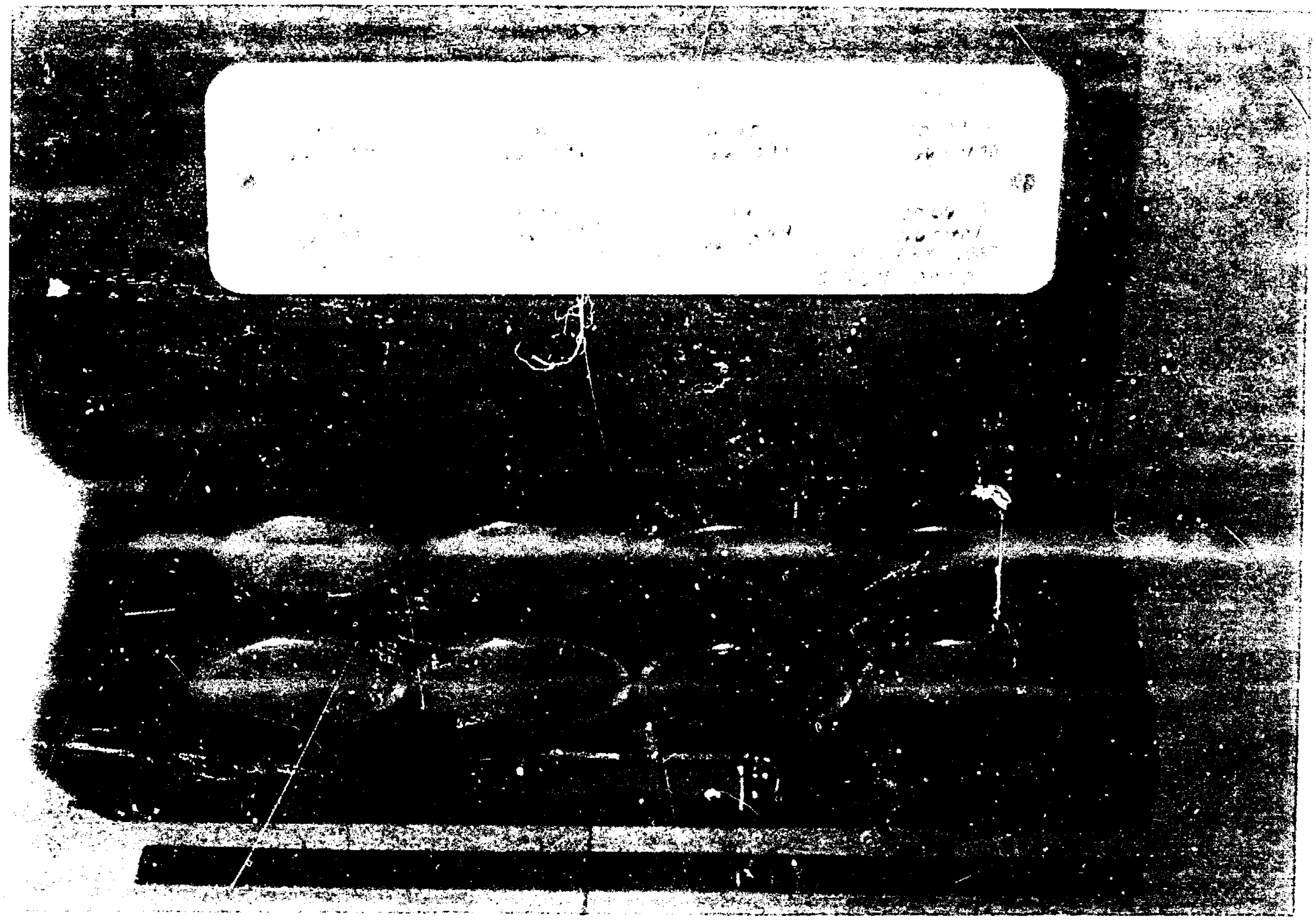


Figure 6. IAEA Calibration Source Set

SECTION III

EXPERIMENTAL METHODS

The measurements of gamma rays and L-X-rays were all performed in air. The distances between the sources and the detector were limited to less than 1 meter to minimize effects of attenuation by air.

The measurements of alpha particles were made with the source and detector placed in an evacuated chamber with small dimensions. Errors in measurement were minimized by separating the source and detector as much as possible.

All counting measurements were recorded with the pulse-height analyzer. Each measurement consisted of 400 channels of information that was transferred to punched paper tape for storage until it could be processed.

1. GAMMA- and L-X-RAY MEASUREMENTS

A sliding, wooden ramp was constructed along the centerline of the photon detector to improve the reproducibility of the measurement geometry. The sources were mounted on small wooden blocks, placed on the ramp (indexed in inches) and aligned parallel to the plane of the detector for counting. The distances between the source and the detector were varied from 3 to 67 centimeters for both plutonium and americium measurements. The counting times were adjusted to permit the collection of approximately equal numbers of counts for all geometries used.

Thirty-four independent measurements were made of the two plutonium sources (P-5611 and P-5612), which represents 240 hours of counting and 10 million counts recorded by the PHA. Eighteen measurements were made of the IAEA Am-241 source (used to establish the efficiency of the detector), which represents 70 hours of counting and 14 million counts recorded by the PHA.

2. ALPHA PARTICLE MEASUREMENTS

The distances between the source and the detector were varied from 3.92 to 4.42 inches during the experiment. The geometry was additionally altered by changing the area presented by the detector to the source. Two sets of measurements were made on each plutonium source. For one measurement set, the total 110-mm^2 area of the detector was left exposed, and for the other set of measurements, the sensitive area of the detector was limited to 31.7 mm^2 with a nylon mask. Thirteen independent measurements were made on the two sources, with more than six million counts recorded by the PHA.

3. DATA PROCESSING

Each pulse-height spectrum was recorded on Tally punched paper tape in binary-coded-decimal form, with an identification number for each measurement punched ahead of each set of data. The data were then transferred to computer cards by a tape-to-card converter, designed and built by the AFWL. The analysis of the data was carried out with a computer program (PhotoPeak Analysis (PPA-II) written by Murphy (Ref. 12). Several background counts of up to 40 hours duration were made with the Ge(Li) detector. The background measurements were then used to correct the photon spectra during the computer analysis. No significant changes in the background spectra were noted during the 45-day period of experimentation.

SECTION IV

DATA ANALYSIS

All of the counting data recorded with the PHA were analyzed with the PhotoPeak Analysis (PPA-II) computer program to determine the count rates in each of the photopeaks. These counting rates were then used (1) to calculate the photopeak efficiency of the detector (from the measurements of the IAEA Am-241 source, which activity was known), and (2) to calculate the activity of the sources of Pu-239 (for alpha particle measurements where efficiency was 100 percent, or for photon measurements after the efficiency of the detector had been determined).

1. PHOTOPEAK ANALYSIS (PPA-II)

The photopeak analysis computer program (PPA-II) used in this experiment is and updated version of an earlier program written by Murphy (Ref. 12). Table I lists the information output by PPA-II. The program operates on a set of data consisting of a 400-channel spectrum from a PHA, the counting time in minutes, and estimates of the channel locations of up to five peaks in the spectrum within 10 percent of their actual location. The program optionally smooths the raw data (done for all data in this experiment) and/or subtracts a background count rate. (Tables II, III, and IV show sample results of smoothing and background subtraction on the same input data. The variations are slight, and accrue from broadening of the data peaks caused by smoothing and by changes in the fit function which is generated, after a background is subtracted.) The time of experiment, time of event or zero time, and the isotope half-life, in deciday form, may also be included in the analysis to correct measurements in which isotope half-life is an important factor. Such corrections were not required for this experiment because Pu-239 has a half-life of 24,400 years (Ref. 1:815) and Am-241 has a 458 year half-life (Ref. 1:847).

The convergence of PPA-II may be assisted with an initial estimate of the expected standard deviation of the count-rate distribution of the data peaks in the spectrum. This feature was particularly useful for this experiment because the gain of the system remained nearly constant for a large number of measurements.

Table I

PHOTOPEAK ANALYSIS (PPA-II) INFORMATION OUTPUT

1. Peak location to the nearest hundredth channel
2. Peak amplitude in cpm/channel
3. Standard deviation of the derived gaussian function in channels
4. Resolution expressed as FWHM (full-width at half maximum amplitude) of the derived gaussian function in percent
5. Peak integral count rate in cpm
6. Peak integral count rate corrected to zero-time
7. A tabulation of the region of interest examined:
   a. channel number, I
   b. background count rate, B(I)
   c. raw or smoothed data points, Y(I)
   d. values of the generated fit function, FIT
   e. values of the derived gaussian, GAUSS
   f. channel-by-channel summation of the data points, SUMY
   g. channel-by-channel summation of the gaussian function, SUMG

Table II

PHOTOPEAK ANALYSIS OF PLUTONIUM SOURCE P-5611 13.51 kev

(Lα) X-RAY WITHOUT SMOOTHING OR BACKGROUND SUBTRACTION

```
033 PU-239 (5611) LA, LB, LG, 51.67, 59.57

ZERO BACKGROUND

TX = -0.        TZ = -0.        DT = 0.
THE DECAY FACTOR = 1.00000000   T1/2 = -0.  DAYS.
THE COUNT TIME IS 40.00 MINUTES.
THE PEAK IS EXPECTED IN CHANNEL 78.00.  (399 CHANNELS)

START PHOTOPEAK ANALYSIS.

THE PEAK APPEARS TO BE NEAR CHANNEL 80.66.
 6 ITERATIONS.

THE PEAK AMPLITUDE IS 182.10 CPM/CH AT CHANNEL 80.70.
THE STANDARD DEVIATION IS 3.22 CHANNELS, ( 9.38 PERCENT FWHM).
THE PHOTOPEAK COUNT-RATE IS 1470.40 CPM AT TX, WHICH CORRESPONDS
TO A COUNT-RATE OF 1.4704E+03 CPM AT TZ.
```

I	B(I)	Y(I)	FIT	GAUSS	SUMY	SUMG
71	0.	64.65	68.85	1.96	64.7	2.0
72	0.	64.98	69.97	4.75	129.6	6.7
73	0.	74.37	74.02	10.47	204.0	17.2
74	0.	86.28	82.83	20.95	290.3	38.1
75	0.	102.28	98.29	38.08	392.5	76.2
76	0.	121.65	121.38	62.85	514.2	139.1
77	0.	152.90	151.05	94.19	667.1	233.3
78	0.	179.55	183.39	128.20	846.6	361.4
79	0.	211.85	211.97	158.45	1058.5	519.9
80	0.	226.00	229.71	177.86	1284.5	697.8
81	0.	232.50	231.48	181.30	1517.0	879.1
82	0.	219.20	216.33	167.83	1736.2	1046.9
83	0.	189.50	187.92	141.09	1925.7	1188.0
84	0.	155.35	152.87	107.72	2081.0	1295.7
85	0.	117.68	118.16	74.68	2198.7	1370.4
86	0.	83.35	88.83	47.02	2282.1	1417.4
87	0.	62.18	67.02	26.88	2344.2	1444.3
88	0.	53.20	52.43	13.96	2397.4	1458.3
89	0.	48.23	43.38	6.58	2445.7	1464.8
90	0.	51.18	37.94	2.82	2496.8	1467.7

Table III

PHOTOPEAK ANALYSIS OF PLUTONIUM SOURCE P-5611 13.51 kev

(Lα) X-RAY WITH SMOOTHING, BUT NO BACKGROUND SUBTRACTION

```
033 PU-239 (5611)  LA, LB, LG, 51.67, 59.57

ZERO BACKGROUND

TX =   -0.        TZ =   -0.        DT =   0.
THE DECAY FACTOR :    1.00000000    T1/2 =    -0.     DAYS.
THE COUNT TIME IS  40.00 MINUTES.
THE SPECTRUM HAS BEEN SMOOTHED.
THE PEAK IS EXPECTED IN CHANNEL  78.00.   (399 CHANNELS)

START PHOTOPEAK ANALYSIS.

THE PEAK APPEARS TO BE NEAR CHANNEL  80.69.
 6 ITERATIONS.

THE PEAK AMPLITUDE IS  180.93 CPM/CH AT CHANNEL  80.70.
THE STANDARD DEVIATION IS  3.26 CHANNELS, (  9.51 PERCENT FWHM).
THE PHOTOPEAK COUNT-RATE IS  1480.55 CPM AT TX, WHICH CORRESPONDS
TO A COUNT-RATE OF 1.4805E+03 CPM AT TZ.
```

I	B(I)	Y(I)	FIT	GAUSS	SUMY	SUMG
70	0.	61.45	69.17	.84	61.5	.8
71	0.	63.36	68.83	2.20	124.8	3.0
72	0.	67.00	70.16	5.20	191.8	8.2
73	0.	74.36	74.50	11.23	266.2	19.5
74	0.	85.17	83.65	22.06	351.4	41.5
75	0.	102.68	99.36	39.47	454.0	81.0
76	0.	124.17	122.48	64.27	578.2	145.3
77	0.	152.16	151.82	95.29	730.4	240.6
78	0.	181.85	183.46	128.62	912.2	369.2
79	0.	209.08	211.22	158.07	1121.3	527.3
80	0.	226.65	228.33	176.86	1347.9	704.1
81	0.	230.14	229.94	180.15	1578.1	884.3
82	0.	216.73	215.18	167.08	1794.8	1051.3
83	0.	190.74	187.48	141.07	1985.6	1192.4
84	0.	154.70	153.17	108.44	2140.3	1300.8
85	0.	117.44	118.94	75.90	2257.7	1376.7
86	0.	86.32	89.72	48.36	2344.0	1425.1
87	0.	63.77	67.73	28.05	2407.8	1453.2
88	0.	52.03	52.81	14.82	2459.8	1468.0
89	0.	48.38	43.43	7.12	2508.2	1475.1
90	0.	50.55	37.74	3.12	2558.7	1478.2

Table IV

PHOTOPEAK ANALYSIS OF PLUTONIUM SOURCE P-5611 13.51 kev

(Lα) X-RAY WITH SMOOTHING AND BACKGROUND SUBTRACTION

```
033 PU-239 (5611)  LA, LB, LG, 51,67, 59,57

019  2450 MIN BACKGROUND                                   *SM*

TX =    -0,          TZ =    -0,          DT =    0,
THE DECAY FACTOR =    1,00000000    T1/2 =    -0,     DAYS,
THE COUNT TIME IS  40,00 MINUTES,
THE SPECTRUM HAS BEEN SMOOTHED,
THE PEAK IS EXPECTED IN CHANNEL  78,00,   (399 CHANNELS)

START PHOTOPEAK ANALYSIS,

THE PEAK APPEARS TO BE NEAR CHANNEL  80,67,
 6 ITERATIONS,

THE PEAK AMPLITUDE IS  180,18 CPM/CH AT CHANNEL  80,69,
THE STANDARD DEVIATION IS  3,32 CHANNELS, (  9,66 PERCENT FWHM),
THE PHOTOPEAK COUNT-RATE IS  1497,38 CPM AT TX, WHICH CORRESPONDS
TO A COUNT-RATE OF 1,4974E+03 CPM AT TZ,
```

I	B(I)	Y(I)	FIT	GAUSS	SUMY	SUMG
70	,77	60,58	67,59	1,00	60,6	1,0
71	,71	62,63	67,46	2,52	123,2	3,5
72	,67	66,39	69,10	5,81	189,6	9,3
73	,63	73,67	73,88	12,24	263,3	21,6
74	,62	85,14	83,52	23,54	348,4	45,1
75	,61	102,09	99,67	41,34	450,5	86,4
76	,60	124,75	122,96	66,27	575,2	152,7
77	,60	152,39	152,05	97,02	727,6	249,7
78	,60	181,65	183,05	129,68	909,3	379,4
79	,60	207,95	209,98	158,25	1117,2	537,7
80	,60	224,73	226,41	176,33	1342,0	714,0
81	,59	227,88	227,81	179,39	1569,8	893,4
82	,57	215,31	213,40	166,63	1785,2	1060,0
83	,56	188,99	186,44	141,32	1974,1	1201,3
84	,56	154,36	152,90	109,43	2128,5	1310,8
85	,56	118,22	119,18	77,37	2246,7	1388,1
86	,55	86,75	90,10	49,94	2333,5	1438,1
87	,55	64,38	67,95	29,43	2397,9	1467,5
88	,55	51,87	52,70	15,84	2449,7	1483,3
89	,55	47,56	42,99	7,78	2497,3	1491,1
90	,56	49,45	37,05	3,49	2546,7	1494,6
91	,56	55,26	33,33	1,43	2602,0	1496,1

Analysis with PPA-II initially provides an improved estimate of the location of each peak maximum by least-squares fitting a parabola to the data points within the location band identified as a part of the given data. A fit function is then generated, which consists of a linear bias term with a superimposed gaussian (normal) distribution fitted to the peak described by the data points. The linear bias term is then subtracted from the fit function and the resulting "pure" gaussian distribution is interpreted as representing the actual distribution of counts occurring in the photoelectric peak (or ionization peak in the case of an alpha-particle spectrum analysis). The location of the maximum of the derived gaussian is then interpreted as the precise location of the photoelectric peak

2. PHOTOPEAK ANALYSIS PLOTTING

A second version of PPA-II, used during this experiment, includes plotting subroutines to permit a visual representation of the analysis. A sample plot is shown in Figure 7. The magnetic tape of this program instructs a Calcomp plotter to plot, index, and label a grid; plot the raw (or smoothed) data points after subtracting background; plot the generated fit function for each peak analyzed in the spectrum; plot the linear bias terms; and plot the resulting gaussian functions representing the photoelectric peaks. The peak amplitudes are prepared for plotting on the basis that the largest peak in the spectrum occurring between 10 and 90 percent of the energy scale is assigned 90 percent of the available amplitude, and all other spectral data are normalized accordingly.

3. CRITERIA FOR DATA REJECTION

Data acceptance or rejection was based on the initial spectral analysis performed by PPA-II. A factor that reflects the "goodness of fit" is the number of iterations required to fit the data with the biased-gaussian fit function (Ref. 12:21). Sets of data requiring more than eight iterations were suspected of containing systematic errors and were rejected from further analysis.

A second factor reflecting the "goodness" of the initial data is the standard deviation of the resulting gaussian distribution of the counts in the full energy peak. For the constant PHA energy scales for the alpha and photon measurements, a nearly constant resolution of particular peaks of the same source spectra in all measurement geometries was expected. This indeed held true, except at very high count rates (>10^5 cpm), as can be seen by a visual comparison of Figures 8 and 9, which show the contrast between high and low count-rate measurements of

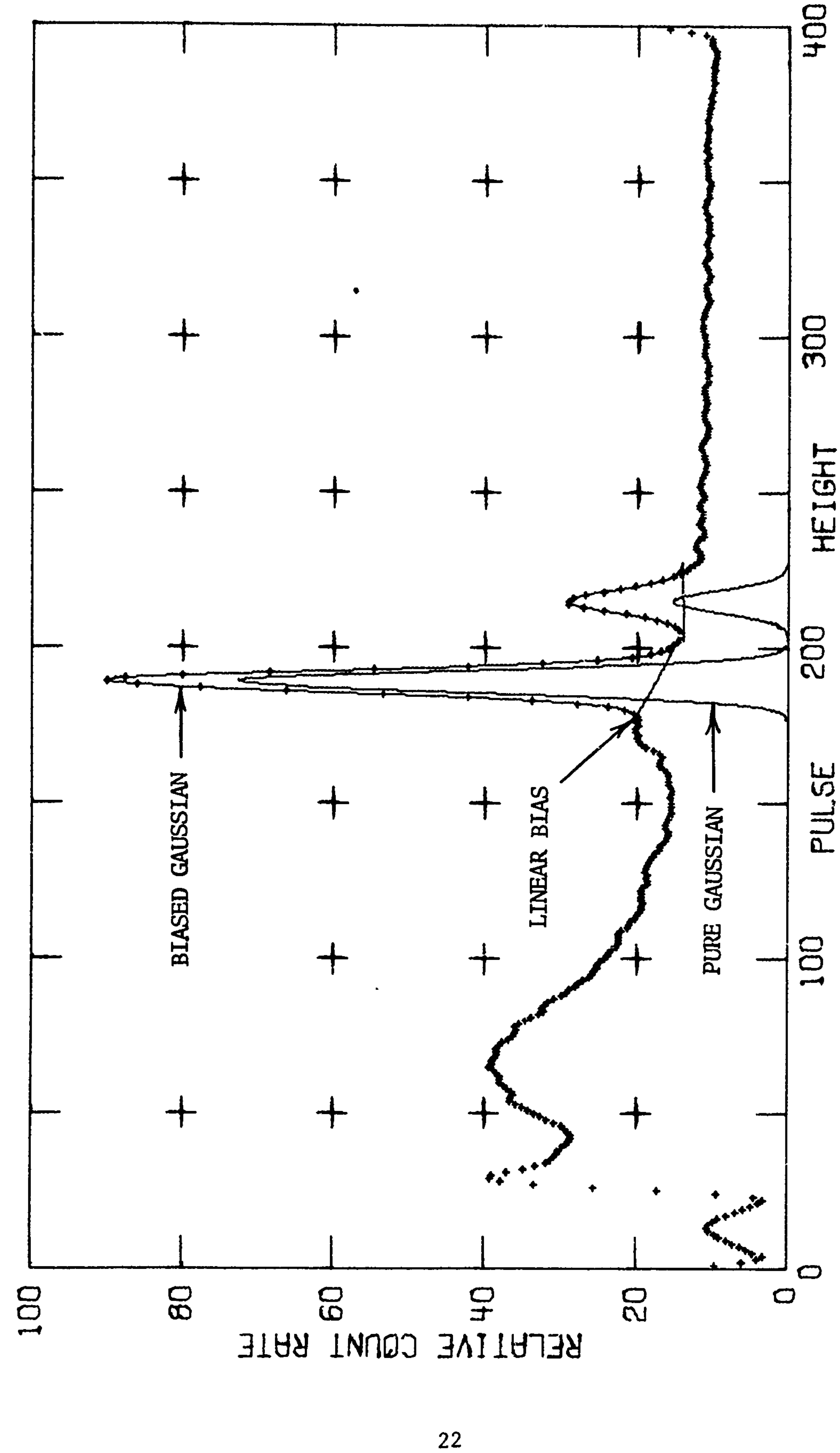


Figure 7. Photopeak Analysis of Cs-137 32.1 and 36.5-kev K-X-Ray Peaks, Showing Biased Gaussian Fit Function, Linear Bias Term, and the Resulting Pure Gaussian Function

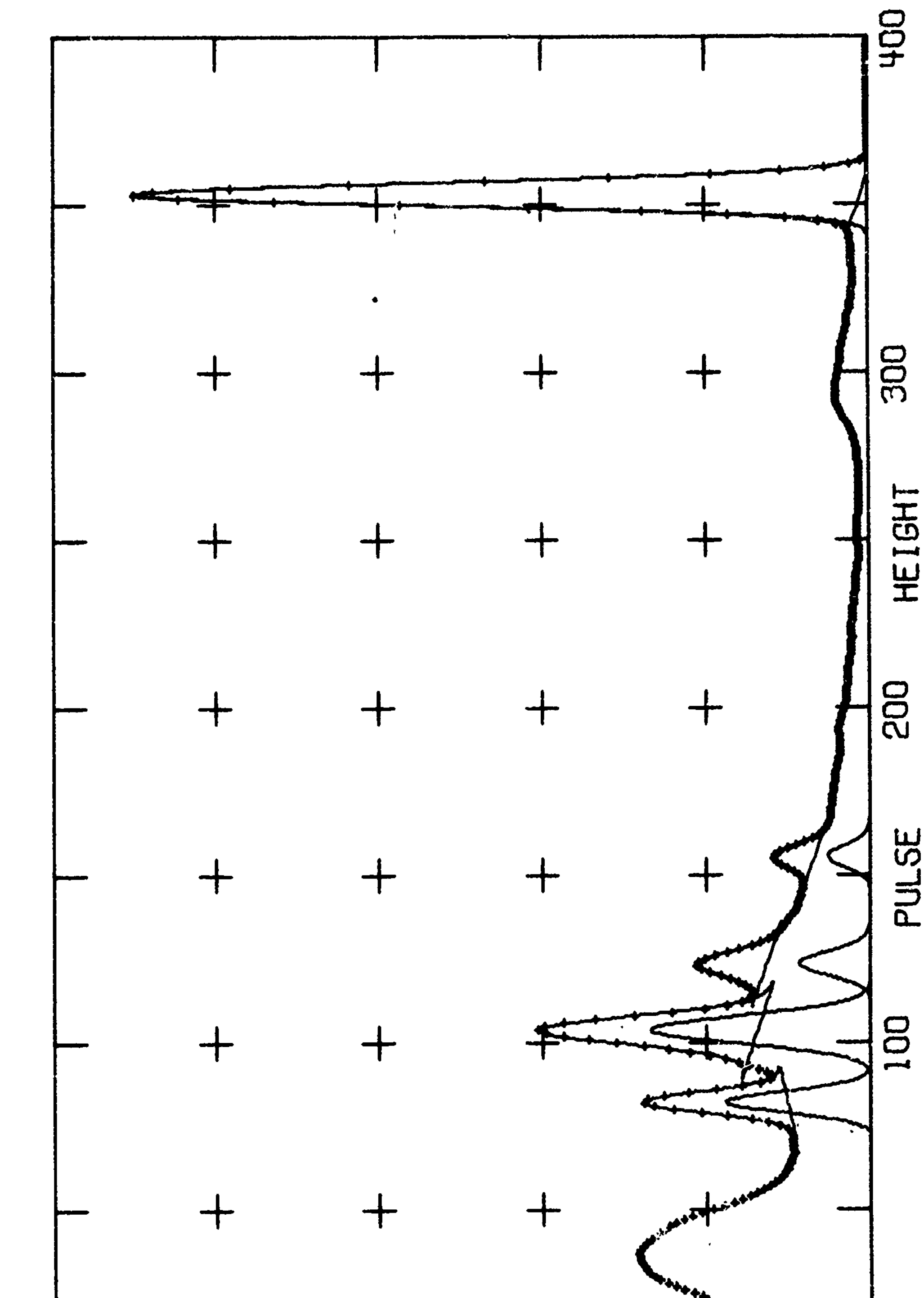


Figure 8. IAEA Am-241 Photopeak Analysis Plot of Photon Spectrum Recorded at Normal Counting Rate (0.169-kev/channel)

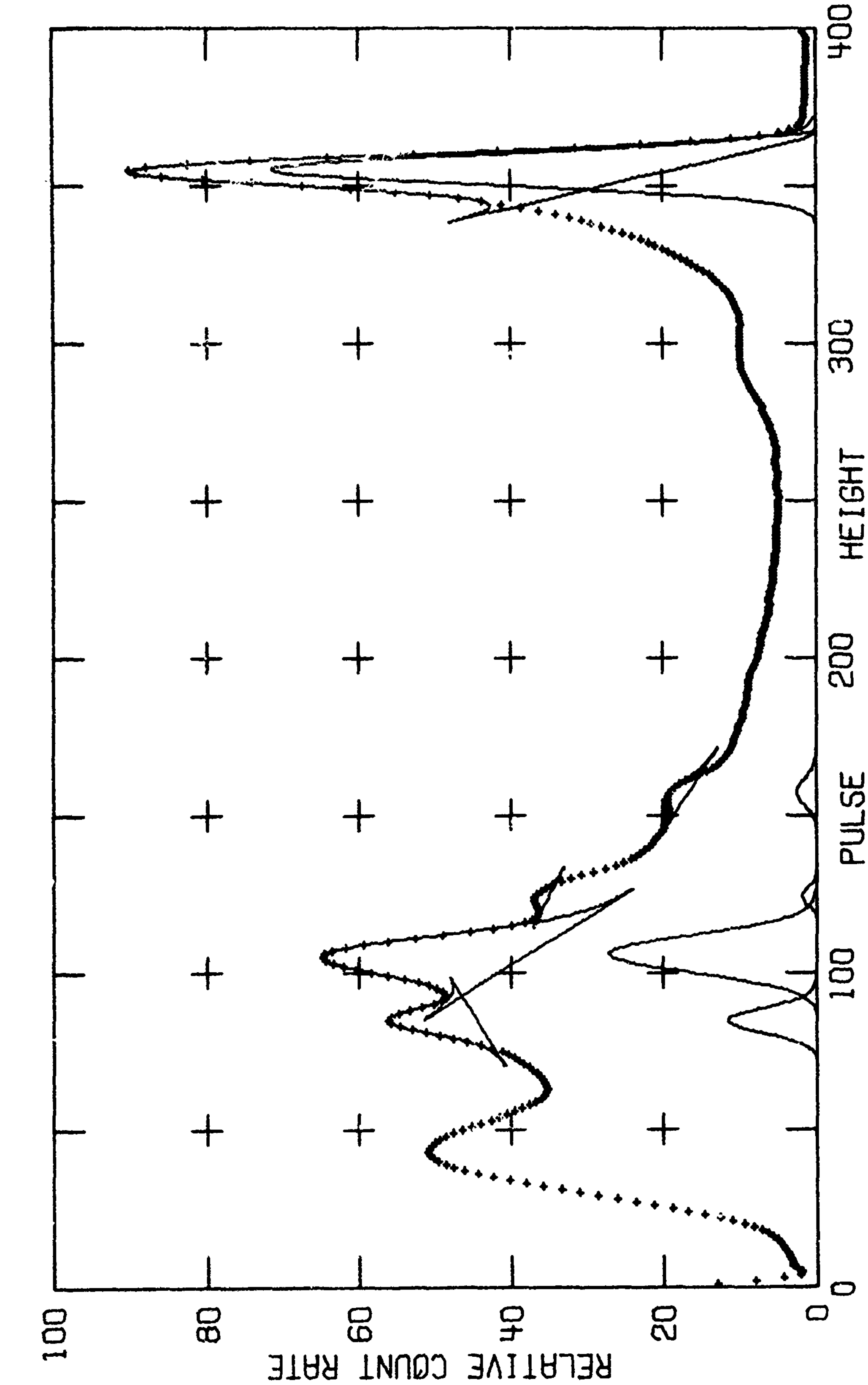


Figure 9. IAEA Am-241 Photopeak Analysis Plot of Photon Spectrum Recorded at Very High Counting Rate (0.169-kev/channel)

the same source. Sets of data that showed a rate-dependent degradation in resolution of more than 10 percent (caused by limitations in the response of the system electronics) were excluded from further analysis.

4. Ge(Li) DETECTOR EFFICIENCY

Determination of the efficiency of the Ge(Li) detector required numerous count-rate measurements of a source with known emission rates at known energies. The integral count rates for each of the three L-X-rays of Am-241 (calibrated IAEA source), and the 26.35 and 59.54-kev gamma rays (Ref. 13:562) were computed with PPA-II. These were considered to be the counting rates actually recorded with the detector. Each of the recorded count rates was then corrected (normalized) to 4-pi geometry and compared with the known activity of the source to determine the efficiency of the detector. The 59.54-kev photoelectric peak in the Am-241 spectrum contained the greatest number of counts and was not subjected to interference from nearby peaks, so it was selected as the best reference for computing the geometric factors for all measurements. These factors were then used to correct the recorded count rates to 4-pi count rates for photopeaks of all energies in the Am-241 spectrum. The mean value for the efficiency of the detector at 59.54 kev was determined by averaging the values of efficiency calculated for all measurements. The mean value for efficiency was then applied to the count rate recorded for each measurement to derive a better value for the geometric factor. This value is hereinafter called the "true" or "actual" geometric factor. Derivation of the actual geometric factors was required because each distance measured between the source and the detector was subject to random errors in measurement. There were also errors in positioning the source relative to the detector centerline, and an uncertainty in the distance between the face of the detector and the beryllium window of the detector housing.

a. Window-to-Detector Distance

All measurements of distance were made from the source to a plastic cover which protected the thin beryllium window to the detector. The distance between the window and the face of the detector was estimated to lie within the range of 1.20 to 1.50 cm by the manufacturer. This estimate was refined with a series of measurements of a point source of radiation, made at various distances along the centerline of the detector. The count rates at a particular energy (under the photopeak) vary inversely with the squares of the distances between the point source and the detector. These distances are obtained easily from a large set of measurements and permit solving for the distances, Δd, to be added to the distances, d_i, measured between the source and the cover of the detector window, as shown in Figure 10.

$$R_i Z_i^2 = R_i (d_i + \Delta d)^2 = \text{constant} \tag{1}$$

where

R_i = ith observed count rate

Z_i = true source-to-detector distance

d_i = measured source-to-window cover distance

Δd = window cover-to-detector distance

For any set of two measurements, i and j

$$\Delta d = \frac{d_i - d_j\left(R_j/R_i\right)^{\frac{1}{2}}}{\left(R_j/R_i\right)^{\frac{1}{2}} - 1} \tag{2}$$

The average value of Δd was calculated from 12 sets of measurements and found to be 2.10 $\pm$ 0.23 cm. A value of 2.13 cm was calculated for Δd from the manufacturer's estimate of 1.50 cm between the beryllium window and the detector, a window thickness of 0.025 cm, a window cover thickness of 0.254 cm, and an assumed penetration distance into the detector of 0.30 cm (half of the thickness of the detector) for 60-kev photons. The mean value for Δd (2.10 cm) calculated from the point-source measurements was added to each of the distances measured for use in calculating the geometry correction factor to apply to each count-rate measurement.

b. Program EFFY

A computer program (EFFY) was written to compute the values of efficiency of the Ge(Li) detector at the energies of the Am-241 photons. The initial calculation performed was for the point-source geometric factors, G_i, for the circular detector. The G_i are the ratios of the angles, Ω_i, subtended by the detector at the source, to the total 4-pi steradian solid angle (Ref. 14:349). The calculation of G_i which corresponds to the ith measurement proceeds as follows:

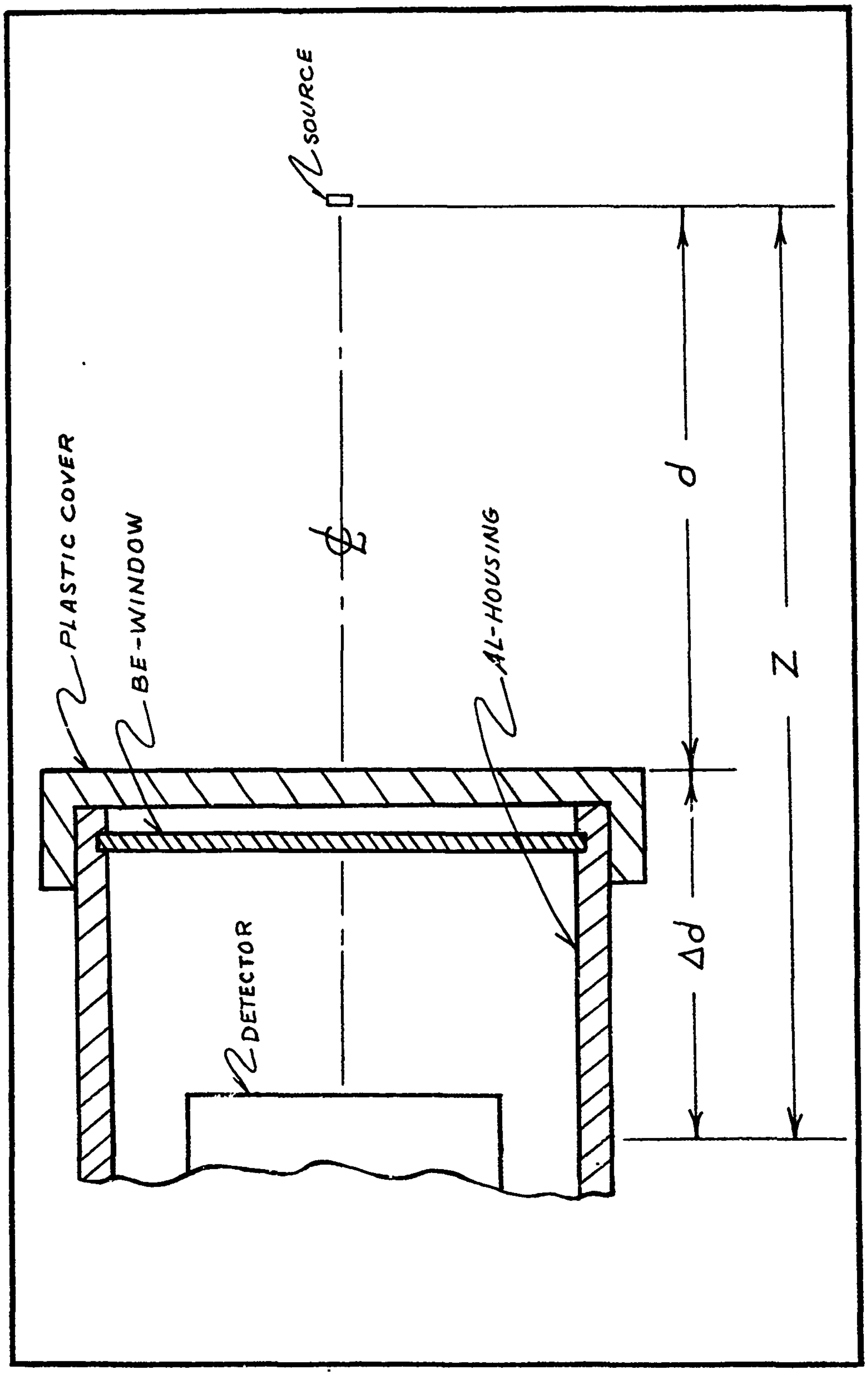


Figure 10. Geometric Relationship of Ge(Li) Detector and Source

$$G_i = \frac{\Omega_i}{4\pi} = \frac{1}{2}\left\{1 - \frac{Z_i}{\left(a^2 + Z_i^2\right)^{\frac{1}{2}}}\right\} \qquad (3)$$

where

Z_i = ith distance between the source and the detector measured along the detector centerline

a = radius of the detector

The IAEA Am-241 source had a calibrated activity of 10.94 $\pm$ 0.036 microcuries. From this activity, A, expressed as a 4-pi disintegration rate, the known fraction (0.359) of 60-kev photons emitted per unit of total activity (alpha) of the source and the computed geometric factors, G_i, the "true" 60-kev gamma-ray emission rates were calculated. The "true" rates, $(R_i)_t$, correspond to the photon rate for each geometry that would have been incident on the detector in the absence of attenuation by air, etc.

$$(R_i)_t = 0.359\ A\ G_i \qquad (4)$$

The photoelectric efficiencies, ϵ_i, of the detector were then calculated from the ratio of the total number of counts determined to be in the integral of the photopeak (calculated by PPA-II), to the total number of photons incident on the detector in the absence of absorption.

$$\epsilon_i = \frac{(R_i)_o}{(R_i)_t} \qquad (5)$$

where

$(R_i)_o$ = the recorded count rate (integral of the photopeak)

A mean value for the photopeak efficiency, $\bar{\epsilon}$, was found by summing the efficiencies for the individual measurements, ϵ, weighted with the total number of counts, R_iT_i, observed for each measurement divided by the corresponding geometric factor, G_i. The sum of the weighted efficiencies was then divided by the sum of the weights.

$$\epsilon = \frac{\sum_{i=1}^{n} \epsilon_i \left(R_i T_i / G_i\right)}{\sum_{i=1}^{n} \left(R_i T_i / G_i\right)} \tag{6}$$

where

T_i = counting time for the ith measurement

R_i = computed photopeak integral count rate

n = 18 (independent measurements)

While it is standard practice to use the total number of counts observed as a weighting factor in calculating mean values based on radiation measurements, the further use of the geometric factor as an additional weight was justified in this case. The near measurements were subject to larger relative errors compared with the far measurements and the magnitudes of the errors are reflected by the magnitudes of the geometric factors. This method of calculation thus provided a greater statistical weight for the distant measurements than for the near measurements.

New values for the geometric factors, G_i', were calculated from the mean value of the photoefficiency of the detector at 60 kev. These were then used to determine the photoefficiencies at other energies in the Am-241 photon spectrum.

$$G_i' = \frac{R_i}{(0.359)\ A\bar{\epsilon}} \tag{7}$$

The calculation of the new geometric factors was justified because the attenuation of 60-kev photons in air over the measurement range of 8 to 67 cm was negligible. According to air-attenuation factors reported by Grodstein (Ref. 15: 50) a variation caused by attenuation of less than 0.003 would be expected over this range. Therefore, the fluctuations in the count rates after they were corrected by 4-pi count rates (in excess of expected counting statistics) could only be caused by errors in measuring the distances between the source and the detector. The use of the adjusted geometric factors had little effect on the other calculations of efficiency. Each value of efficiency calculated was merely closer to the mean value for the set of measurements.

New values for distance (Z_i') between the source and the detector were calculated from the adjusted geometric factors for comparison with the measured values and to verify that the fluctuations of the measured distances were in fact statistical in nature (did not include systematic errors).

$$Z_i' = \frac{a(1 - 2G_i')}{2\left(G_i'(1 - G_i')\right)^{\frac{1}{2}}} \tag{8}$$

The standard deviation of the measured distances from the computed distances is given by

$$\sigma_z = \left\{\frac{\sum_{i=1}^{n} \left(Z_i - Z_i'\right)^2}{n}\right\}^{\frac{1}{2}} \tag{9}$$

The value computed for the standard deviation was 0.725 cm. Twelve measurements showed deviations of less than σ_z, three more were within $2\sigma_z$, and one was slightly greater than $2\sigma_z$. These results adequately satisfied the assumption that the errors in measurement were indeed random. This is emphasized here, because such a check could not be readily performed on the measurements of the plutonium sources because of the complexity of the geometric factors.

The adjusted geometric factors (G_i') were then used to compute the efficiencies of the detector for the remaining energies in the Am-241 photon spectrum. For each energy, it was necessary to adjust the original activity of the source by the fraction of photon activity relative to the unit source activity. The energies and relative activities calculated from values reported by Magnussen (Ref. 16:164), based on unit activity for the 60-kev photon, are 13.9 kev (0.375); 17.8 kev (0.512); 20.8 kev (0.138); and 26.35 kev (0.07). The weighted standard deviation of the efficiencies was computed from the relation

$$\sigma_\epsilon = \left\{\frac{\sum_{i=1}^{n} \left(\bar{\epsilon} - \epsilon_i\right)^2 R_i T_i / G_i}{\frac{n-1}{n} \sum_{i=1}^{n} \left(R_i T_i / G_i\right)}\right\}^{1/2} \tag{10}$$

The original geometric factors were used to compute the standard deviation for the detector efficiency at 60 kev and the adjusted geometric factors were used to compute the standard deviations at other energies. The results for all energies are given in Table V and samples of information output by program EFFY are listed in Appendix IV.

Table V

Ge(Li) DETECTOR PHOTOELECTRIC EFFICIENCIES FOR Am-241 PHOTONS

Energy (kev)*	Mean Photopeak Efficiency**	Std. Dev.**
13.9 ± 0.1	0.306	0.015
17.8 ± 0.1	0.424	0.009
20.8 ± 0.1	0.454	0.018
26.348 ± 0.01	0.485	0.018
59.543 ± 0.015	0.608	0.033

* Ref. 11:562

** Ref. Appendix IV

c. Program POLY

The computer program POLY (also written by Murphy, but unpublished) was used to obtain a least-squares fit cubic polynomial, which expressed detector efficiency as a function of photon energy E, over the range of 13.9 to 59.543 kev.

$$\epsilon(E) = \sum_{i=1}^{N} C_i E^{N-1} \tag{11}$$

where

$N = 4$

$C_1 = -6.64454 \times 10^{-1}$

$C_2 = 1.11248 \times 10^{-1}$

$C_3 = 3.40975 \times 10^{-3}$

$C_4 = 3.19147 \times 10^{-5}$

The polynomial generated contained a relative minimum between the energies of 26.35 and 59.54 kev because an insufficient number of data points was used. Therefore, the efficiency in this energy interval was obtained by linear interpolation. This was of minor consequence because the energies of primary interest in this experiment were below 26 kev.

d. Plutonium Photon Energy Determination

The energies of the photons emitted by plutonium were calculated from the pulse-height analyzer energy scale established by the location of the 59.543-kev gamma ray photopeak of Am-241. The precise locations were determined by PPA-II to the nearest hundredth channel. The results presented in Table VI were calculated from six successive measurements of source P-5612 (Pu-239). The efficiencies for detection of the photons from plutonium were calculated by use of equation (11), except the efficiency for the 51.56-kev gamma ray, which was obtained by linear interpolation.

Table VI

Ge(Li) DETECTOR PHOTOPEAK EFFICIENCIES FOR PLUTONIUM PHOTONS

Peak Channel Location	Energy (kev)	Efficiency
80.20	13.51	0.295
101.10	17.03	0.399
119.70	20.16	0.446
306.09	51.56	0.579
353.48	59.543 (Am-241)	0.608

5. PLUTONIUM PHOTON ACTIVITY ANALYSIS

The total rates of emission of L-X-rays from Pu-239 were obtained from the areas under the photopeaks, corrected for geometry and detector efficiency, and additionally corrected for contributions from the Am-241 and Pu-240 impurities in the sources. The integral count rate for each photopeak in the plutonium photon spectrum was computed with PPA-II. The values obtained with PPA-II were used as the observed count rates in a special purpose computer program called PLUTO, which was written to apply efficiency and geometry corrections to yield the total (4-pi) emission rates for the two plutonium sources (P-5611 and P-5612). The results of the computations accomplished by the PLUTO program were then corrected for impurities in the sources to yield the total photon emission rates resulting only from the presence of Pu-239.

a. Program PLUTO

The PLUTO computer program is similar to the EFFY program in its operations. Where program EFFY used the 60-kev gamma-ray activity as a reference value on which to base calculations of the "true" geometric factors, program PLUTO made use of the 17.03-kev L_β-X-ray of plutonium for the same purpose. The lower energy photon is subject to more attenuation by air than the 60-kev gamma ray, but the Am-241 content of the sources was too small for the 60-kev gamma ray to be used as a reliable reference.

The operations of the PLUTO program were first carried out on the data for the L_β-X-ray, and then on the data for other energies in the same photon spectrum. Each analysis required the following data: the radius of the detector, the counting time for each measurement in minutes, and the measured distances between the source and the detector for the entire set of measurements. This information was followed with the energy of the photon (for identification), the detector efficiency at that energy, and the observed count rates.

The initial computation was performed to find the geometric factors, G_i, from the measured distances, Z_i, between the source and the detector, the radius of the detector, a, and the radius of the source, b.

$$G_i = 1/2\left\{1 - \frac{Z_i}{\left(a^2 + Z_i^2\right)^{1/2}}\right\} - 3/16\left\{\frac{a^2b^2Z_i}{\left(a^2 + Z_i^2\right)^{5/2}}\right\} + 5/32\left\{\frac{a^2b^4Z_i}{\left(a^2 + Z_i^2\right)^{9/2}}\left(Z_i^2 - (3/4)a^2\right)\right\} \tag{12}$$

This expression for calculating the geometric factors was taken from Jaffey (Ref. 14:351), and includes the first two integrals of a binomial expansion of the point-source geometric factor. Additional terms were not required because the source-to-detector distances were significantly larger than the radii of either the source or the detector. The computed geometric factors, G_i, and the known photopeak efficiency of the detector enabled computation of the mean 4-pi emission rate, $\overline{R}_{4\pi}$, with the same method of weighting as was used with program EFFY.

$$\overline{R}_{4\pi} = \frac{\sum_{i=1}^{n} \left(R_i/\epsilon G_i\right)\left(R_i T_i/G_i\right)}{\sum_{i=1}^{n} \left(R_i T_i/G_i\right)} \tag{13}$$

where

n = number of measurements in the set

R_i = observed count rate of the ith measurement

T_i = counting time for the ith measurement

ϵ = photopeak efficiency of the detector

The experimental standard deviation, σ_{exp}, for each set of measurements, was computed from the sum of the squares of the deviations of each measurement from the mean 4-pi emission rate calculated with equation (13).

$$\sigma_{exp} = \left\{ \frac{\sum_{i=1}^{n} \left(\overline{R}_{4\pi} - R_i/\epsilon G_i\right)^2 \left(R_i T_i/G_i\right)}{\frac{n-1}{n} \sum_{i=1}^{n} \left(R_i T_i/G_i\right)} \right\}^{\frac{1}{2}} \tag{14}$$

New geometric factors, G_i', were calculated from the mean 4-pi emission rate of the reference energy photon (17.03 kev), similar to the procedure followed with program EFFY. The new geometric factors were then used to find the 4-pi count rates and the associated standard deviations for the photons of other energies in the same plutonium spectrum (same set of measurements). The 4-pi count rates computed with program PLUTO for the two plutonium sources (P-5611 and

P-5612) are listed in Table VII. Program PLUTO is listed in Appendix III, and sample results of its output are tabulated in Appendix VI.

Table VII

PLUTONIUM SOURCE 4-PI COUNT RATES DETERMINED WITH PROGRAM PLUTO

Energy (kev)	Source P-5611* (cpm x 10^6)	Source P-5612* (cpm x 10^6)
13.51	0.646 $\pm$ 0.022	0.970 $\pm$ 0.037
17.03	0.795 **	1.221 **
20.16	0.176 $\pm$ 0.005	0.274 $\pm$ 0.013
51.56	0.010 $\pm$ 0.002	0.014 $\pm$ 0.003
59.54	0.042 $\pm$ 0.003	0.131 $\pm$ 0.043

* Ref. Appendix VI

** Reference activity used to calculate geometric correction factors to apply to count rates at other energies

b. Corrections for Impurities

The plutonium sources (P-5611 and P-5612) contained some impurities in concentrations that were known, while others became evident during the experiment. The L-X-ray count rates measured with the detection system and subjected to analysis with the computer required corrections for these impurities, to arrive at the emission rates of L-X-rays caused by the presence of Pu-239 only. The expression describing this correction is given by

$$R_{P239} = R_T\left(1 - F_{P241} - F_{A241} - F_{P240}\right) \tag{15}$$

where

R_{P239} = Rate of L-X-rays emitted only by Pu-239 in the source

R_T = Rate of total L-X-ray emission by the source

F_{P241} = Fraction of L-X-rays caused by the presence of Pu-241 in the source

F_{A241} = Fraction of L-X-rays caused by the presence of Am-241 in the source

F_{P240} = Fraction of L-X-rays caused by the presence of Pu-240 in the source

The ensuing paragraphs describe the corrections made for each impurity known to be present in the sources.

(1) Correction for Pu-241 Impurity

The L-X-ray data did not require a correction for the presence of Pu-241, because of its low abundance in the sample and its long, alpha-disintegration half-life. Pu-241 decays to U-237 by alpha-particle emission with a half-life of 5 x 10^5 years (Ref. 1:828). If each alpha-disintegration were followed by emission of an L-X-ray, the ratio of Pu-241 L-X-rays to those from Pu-239 could be a maximum of 0.000146. (A Pu-239 L-X-ray to alpha-particle ratio of 0.05 was assumed for the calculation). Other data in this experiment are believed accurate only to the third significant figure. Consequently, the L-X-ray contribution of Pu-241 was neglected because of its insignificant magnitude.

(2) Correction for Am-241 Impurity

The contribution of L-X-rays from Am-241 was of sufficient magnitude to require correction. The correction was necessitated by the near coincidence of the corresponding Am-241 and plutonium L-X-ray energies (superimposition of the photopeaks). The photon activities in Table VII and the known $L_\alpha/L_\beta/L_\gamma$ fractions of 0.375/0.512/0.138 (Ref. 14:164) for Am-241 relative to a unit activity for its 60-kev gamma ray were used to compute the appropriate corrections for the Am-241 content of the sources. The resulting photon activities of the two plutonium sources (P-5611 and P-5612) are given in Table VIII.

Table VIII

PLUTONIUM SOURCE 4-PI COUNT RATES AFTER Am-241 SUBTRACTED

Energy (kev)	Source P-5611 (cpm x 10^6)	Source P-5612 (cpm x 10^6)
13.51	0.631 ± 0.027	0.921 ± 0.046
17.03	0.774 ± 0.021	1.155 ± 0.031
20.16	0.170 ± 0.012	0.256 ± 0.021
51.56	0.010 ± 0.002	0.144 ± 0.003

(3) Correction for Pu-240 Impurity

The contribution from Pu-240 to the L-X-ray spectra of the two sources was calculated from the isotope percentage of 0.752 ± 0.015 percent (furnished by the manufacturer), a half-life of 6580 years (Ref. 1:823), and the L-X-ray to alpha-particle ratio of 0.109 (Ref. 5:284). These values were used to correct the gross spectrum because the distribution of the spectral components (percentages of L_α, L_β, and L_γ-X-rays) of Pu-240 was not known. The corrections were applied to the values in Table VIII and the resulting activities for the Pu-239 isotope, only, appear in Table IX.

Table IX

PLUTONIUM SOURCE 4-PI PHOTON COUNT RATES AFTER Pu-240 SUBTRACTED (Pu-239 ONLY)

Energy (kev)	Source P-5611 (cpm x 10^6)	Source P-5612 (cpm x 10^6)
13.51	0.591 ± 0.027	0.863 ± 0.046
17.03	0.726 ± 0.021	1.083 ± 0.031
20.16	0.159 ± 0.012	0.240 ± 0.021
51.56	0.010 ± 0.002	0.014 ± 0.003
Total L-X-ray:	1.476 ± 0.036	2.186 ± 0.059

6. PLUTONIUM ALPHA ACTIVITY ANALYSIS

a. Computer Program ALFY

A computer program (ALFY) was written to correct the alpha-particle count rates, recorded by the detector, to 4-pi disintegration rates for both plutonium sources (P-5611 and P-5612). A single peak in each measurement spectrum was analyzed with the PPA-II analysis code. This peak represented the response of the detector to the multi-line spectrum of the several plutonium isotopes that were present in the sources. The detection system was unable to clearly resolve each line in the spectrum, so the response was purposely degraded further (by operating the detector at room temperature) to include all of the spectral components in a single, broad peak. This was fitted with a biased gaussian function and integrated by the PPA-II analysis program to yield the count rate recorded by the detector, which was then corrected for geometry by program ALFY.

The mathematical operations in the ALFY program were identical to those carried out by the PLUTO program and will not be repeated here. The basic difference in the two programs was the restriction of the ALFY program to operation on only one count-rate integral (from the PPA-II analysis) for each spectral measurement. In contrast, the PLUTO program was designed to use the mean 4-pi count rate of the dominant energy peak in the photon spectra to generate a second set of geometric factors which were then applied to the count rates corresponding to other energy photons in the same spectra.

The efficiency of the silicon detector for alpha particles was assumed to be 100 percent. This assumption was believed valid because of the small-angle geometry used for the measurements. Alpha particle penetration into the detector was restricted to directions near the perpendicular to the plane of the detector, so that a minimum of inactive material would be traversed. Separate determinations of the activity of source S-307 (Am-241) were made with the calibrated photon detection system and with the alpha particle detection system to verify the assumed efficiency of the alpha detector. The results agreed within 2 percent. The ALFY program is listed in Appendix II and samples of its information output for the two plutonium sources appear in Appendix V.

b. Calculation of Gross Alpha Activity

Two sets of measurements of alpha particle activity were made on each of the plutonium sources (P-5611 and P-5612). A different geometric configuration was used to obtain each set of measurements. One set was obtained with the total area (1.10-cm^2) of the detector exposed to the source, while the other set was made with the area of the detector reduced to 0.317-cm^2 with a nylon mask.

Both sets of measurements were combined to determine the composite mean alpha activity for each source. The mean alpha particle activity computed for each set of measurements was weighted, and the weighted activities were summed and divided by the sum of the weighting factors. The weighting factors used for each measurement set consisted of the total number of counts registered by the detection system normalized to 4-pi geometry. The geometric correction factors were included to lend additional weight to measurements made with larger distances between the source and the detector. (Increasing the distance between the source and the detector helped to compensate for errors in positioning the source along the detector centerline.) The error terms associated with each set of measurements were squared, similarly weighted, summed, and divided by the sum of the weight factors, and the square root taken to yield a composite standard deviation for the combined sets of measurements. The alpha activities for each source as measured and computed, along with the composite activities for both sources, are listed in Table X.

Table X

PLUTONIUM ALPHA ACTIVITIES

Exposed Detector Area (cm^2)	Source P-5611		Source P-5612	
	Rate (dpm x 10^7)	Activity (μCi)	Rate (dpm x 10^7)	Activity (μCi)
0.317	3.10 $\pm$ 0.01	13.9	4.83 $\pm$ 0.06	21.8
1.10	3.23 $\pm$ 0.02	14.6	5.08 $\pm$ 0.01	22.9
Composite	3.21 $\pm$ 0.02	14.5	4.94 $\pm$ 0.01	22.2

c. Correction for Source Impurities

It was shown in the section on photon analysis that there was no need to correct for the Pu-241 in the sample. Moreover, for the alpha case, there was no need to correct for Am-241, because its small ionization peak was sufficiently removed from the ionization peak of the plutonium isotopes (330-kev separation) to be excluded from the data analysis with PPA-II. However, according to Leang (Ref. 17:3157) the Pu-240 dominant energy is within 20 kev of the dominant energy of Pu-239 and must be assumed to have been included in the analysis. The required correction for the presence of Pu-240 in the sources was derived from the ratio of the half-lives of Pu-239 (24,400 years) and Pu-240 (6580 years) and their relative abundances (0.99233 and 0.00752 respectively) as furnished by the manufacturer. Based on the given numbers, 2.81 percent of the disintegrations occurring in the source are attributable to the Pu-240. The corrected alpha activities of the sources ascribed to the Pu-239, only, are P-5612, 4.80 $\pm$ 0.01 x 10^7 dpm; and P-5611, 3.12 $\pm$ 0.02 x 10^7 dpm.

7. L-X-RAY/ALPHA-PARTICLE RATIO

The L-X-ray/alpha-particle emission ratio for Pu-239 was calculated separately for each of the two sources to yield P-5611 L-X-ray/alpha ratio, 0.0474 ± 0.0015; and P-5612 L-X-ray/alpha ratio, 0.0456 ± 0.0013. The composite L-X-ray/alpha-particle emission ratio for the two sources was obtained by summing the values for each source, weighted with the total number of counts divided by the summation of the geometric factors overall measurements. The weighted ratios were then added and divided by the sum of the weighting factors. Table XI lists the values calculated for the ratios of photons to alpha particles emitted by Pu-239 and relative intensities recorded for the L_α, L_β, and L_γ X-ray groups.

Table XI

RATIOS OF PHOTONS TO ALPHA PARTICLES AND RELATIVE INTENSITIES OF L-X-RAY GROUPS FOR Pu-239

Pu-239 Source	Ratios		
	L-X-Ray/ α-particle (%)	γ-Ray (51.6-kev)/ α-particle (%)	$(L_\alpha/L_\beta/L_\gamma)$ X-Ray Group Intensities
P-5611	4.74 ± 0.15	.0321 ± .0064	1.00/1.23/0.27
P-5612	4.56 ± 0.13	.0292 ± .0063	1.00/1.25/0.28
Composite	4.59 ± 0.14	.0304 ± .0057	1.00/1.23/0.27

SECTION V

DISCUSSION OF RESULTS

Despite the difficulties inherent to the performance of an absolute counting experiment, these results agree well with those obtained by other experimenters. In this experiment, a ratio of 0.0459 ± 0.0014 was determined for L-X-rays to alpha particles emitted by Pu-239. This value is within 5.4 percent of the ratio 0.0485 ± 0.0004, determined by Swinth (Ref. 5) in 1967 with an alpha particle, photon coincidence-counting method.

There were two discrepancies worthy of elaboration: (1) the values for the ratio of L-X-rays to alpha particles for the two Pu-239 sources differed by 3 percent; and (2) the alpha activities of the sources of Pu-239 were 30 percent higher than those claimed by the manufacturer.

1. RATIO OF L-X-RAYS TO ALPHA PARTICLES

The difference (about 3 percent) in the values obtained for the ratio of L-X-rays to alpha particles for the two plutonium sources probably resulted from (1) a difference in the corrections made on the count rates (recorded by the PHA) of the two plutonium sources because of the method of weighting used to determine the efficiency of the photon detector, and (2) problems in the analysis caused by interference between nearby X-ray peaks in the same pulse-height spectrum.

a. Overcorrection of Count Rates

The efficiency of the photon detection system was determined from a large set of measurements of the calibration source of americium. The value of efficiency for each measurement was weighted with a factor to compensate for the geometry of the measurement (see Eq. (6)). The weighted values were then summed and divided by the sum of the weight factors. This obtained a value for efficiency that corresponded to the mean geometry of the set of measurements, with no attempt made to compensate the count rates at lower energies for attenuation by air. The efficiency factors calculated from the derived polynomial (see Eq. (11)) for the energies of the plutonium photons, then corresponded to the same average geometry as was used to measure the count rates from Am-241. That geometry was equivalent to a distance of 25 cm between the source and detector.

The average distances between the plutonium sources and the detector were 18 cm for source P-5612 and 12 cm for source P-5611.

The factors calculated for efficiency of the detector at L-X-ray energies and a measurement distance of 25 cm are slightly lower than those that should be used at lesser distances because of the effects of attenuation by air (more pronounced on the photons with lower energy). The use of the polynomial derived from the efficiency factors calculated for Am-241 photons resulted in an overcorrection of the count rates obtained for the L-X-rays from the two plutonium sources at the lesser average distances. The magnitude of the overcorrection ranged between 1 and 2 percent (depending on the energy of the photon), based on values for the total mass attenuation coefficients in air reported by Grodstein (Ref. 15:50).

b. Interference Between Peaks

The plots of the photopeak analysis (PPA-II) in Figures 11 and 12 show a small amount of overlap of the derived gaussian functions for adjacent peaks. This phenomenon resulted because each of the three major groups of L-X-rays was treated as a monoenergetic photon, when in fact it is composed of photons with many discrete energies. The gaussian approximation was applied to the multi-energy groups of X-rays because the individual component energies could not be resolved by the detection system.

2. ALPHA ACTIVITY

The large differences (about 30 percent) between the alpha activities of the two plutonium sources as reported by the manufacturer (10.2 and 15.8 μCi) and as determined in this experiment (14.5 and 22.2 μCi) is attributed to the heat treatment given the sources by the manufacturer. The heat treatment either ingrains the plutonium with the structure of the nickel base metal, or forms a thick (in terms of penetration by alpha particles) oxide over the plating. In either case, the effect is quite observable when the results of the two methods of counting are compared (50 percent geometry used by the manufacturer and less than 1 percent goemetry used in this experiment). The results indicate that the majority of alpha particles escaping from the surface of the source are confined to deviations of small angles from the direction normal to the surface, and that few alpha particles manage to penetrate the barrier that exists at angles near the plane of the source.

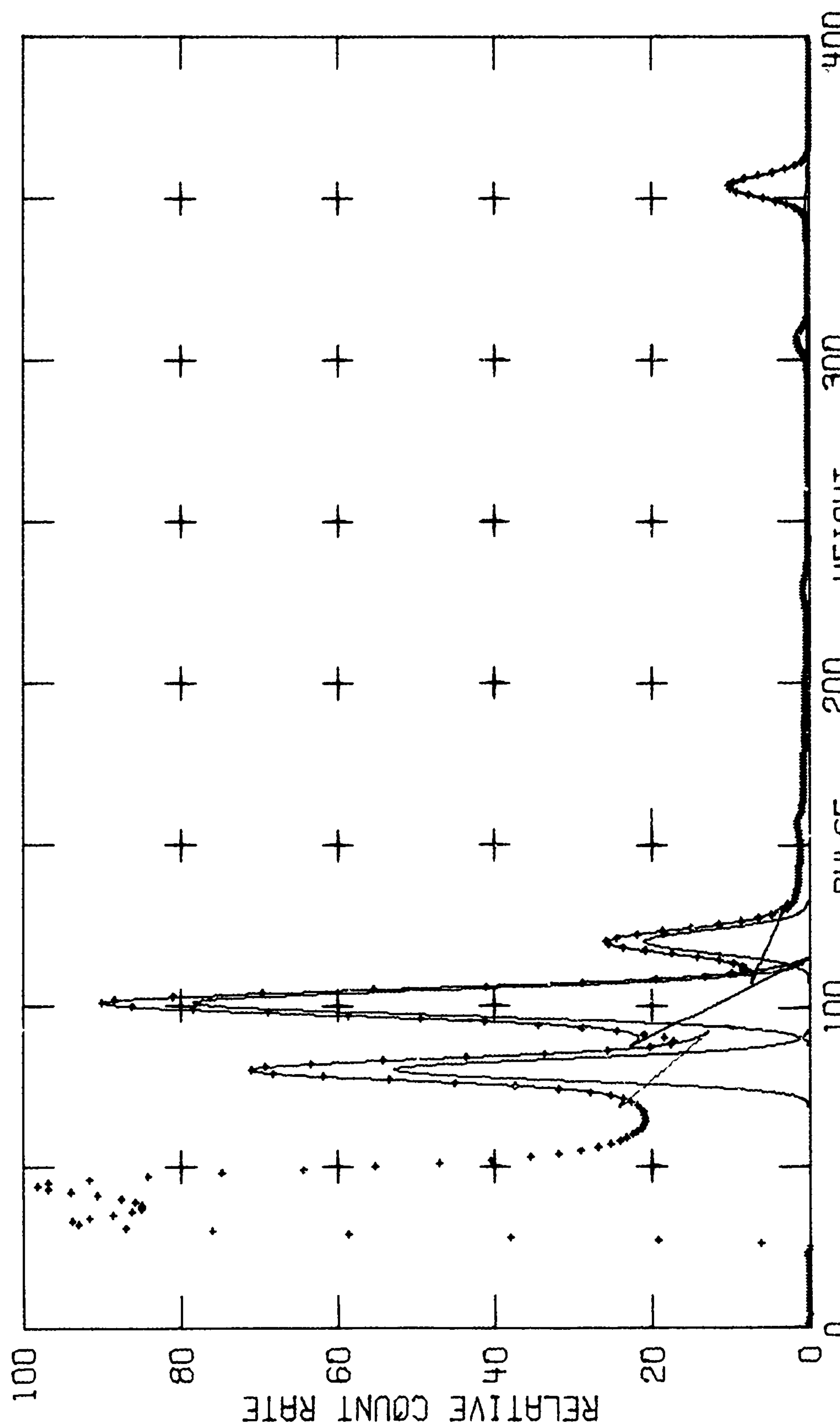


Figure 11. Photopeak Analysis Plot of Plutonium Source P-5612 Smoothed Photon Spectrum with Background Subtracted (0.169-kev/channel)

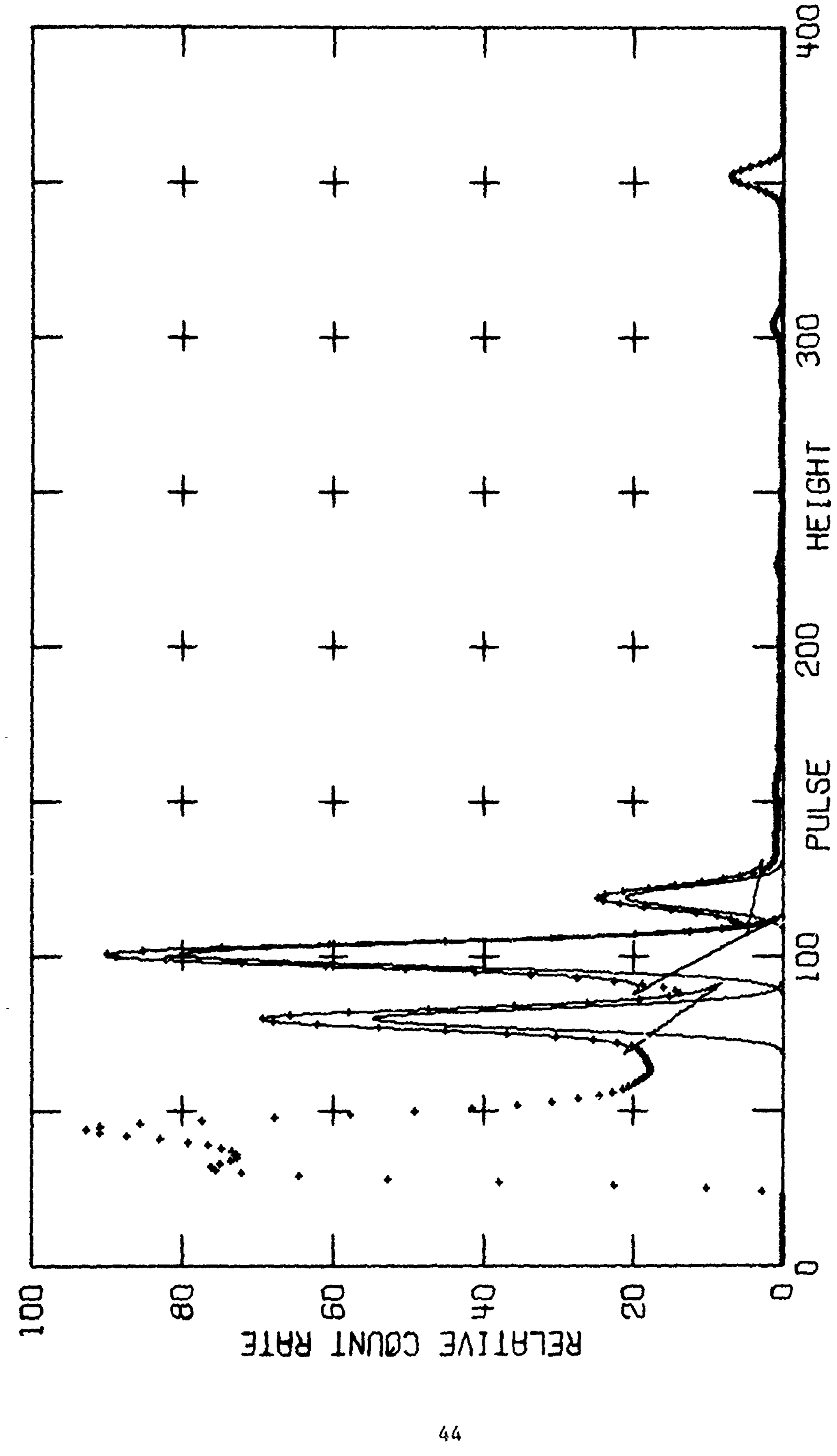


Figure 12. Photopeak Analysis Plot of Plutonium Source P-5611 Smoothed Photon Spectrum with Background Subtracted (0.169-kev/channel)

Another indication of the surface-barriers of the sources was the differences in the locations of the energy peaks of the plutonium alpha particles in the spectra for the two sources (when counted with the same gain for the system) as shown in the output results of the photopeak analysis (PPA-II) computer program in Tables XII and XIII, and the corresponding plots of the same analyses shown in Figures 13 and 14. The reduced pulse height and the spreading of the peak distributions of counts are both indicative of the absorption of alpha particle energy at the surface of the source. An energy scale of 17.4 kev per channel was established with the thin source of alpha particles, S-307 (Am-241). The 5.48-Mev energy alpha particle peak was placed in channel 315 of the PHA, with a baseline setting of zero. (A sample output list of the analysis of S-307 performed by PPA-II is given in Table XIV.) The plutonium sources (P-5611 and P-5612) were then counted with identical gain settings for the system. The 5.15-Mev energy peak, dominant in Pu-239, was expected to be centered in channel 296 with the energy scale that had been established with the source of Am-241, but instead fell in channel 273 for P-5611 and in channel 279 for P-5612. Thus, both sources displayed a pulse height reduced by 300 to 400 kev for the alpha particle peak at 5.15 Mev.

Table XII

ANALYSIS OF PLUTONIUM SOURCE P-5611 ALPHA SPECTRUM

WITH SMOOTHED INPUT DATA

239 P-5611 ALPHA TOT AREA S-D 4.42IN. 21 DEC 67

ZERO BACKGROUND

TX = -0. TZ = -0. DT = 0.
THE DECAY FACTOR = 1.00000000 T1/2 = -0. DAYS.
THE COUNT TIME IS 8.32 MINUTES.
THE SPECTRUM HAS BEEN SMOOTHED.
THE PEAK IS EXPECTED IN CHANNEL 276.00. (399 CHANNELS)
START PHOTOPEAK ANALYSIS.

THE PEAK APPEARS TO BE NEAR CHANNEL 272.90.
5 ITERATIONS.
THE PEAK AMPLITUDE IS 1892.02 CPM/CH AT CHANNEL 272.58.
THE STANDARD DEVIATION IS 4.59 CHANNELS, (3.96 PERCENT FWHM).
THE PHOTOPEAK COUNT-RATE IS 21780.27 CPM AT TX, WHICH CORRESPONDS
TO A COUNT-RATE OF 2.1780E+04 CPM AT TZ.

I	B(I)	Y(I)	FIT	GAUSS	SUMY	SUMG
258	0.	27.35	-11.89	12.22	27.4	12.2
259	0.	37.02	2.10	23.83	64.4	36.0
260	0.	53.23	24.97	44.31	117.6	80.4
261	0.	81.63	61.62	78.58	199.2	158.9
262	0.	127.45	118.33	132.91	326.7	291.9
263	0.	201.66	202.19	214.39	528.3	506.2
264	0.	312.23	319.99	329.81	840.6	836.1
265	0.	468.93	476.44	483.88	1309.5	1319.9
266	0.	666.74	671.97	677.03	1976.2	1997.0
267	0.	906.23	900.74	903.41	2882.5	2900.4
268	0.	1156.58	1149.38	1149.68	4039.0	4050.1
269	0.	1405.24	1397.40	1395.32	5444.3	5445.4
270	0.	1617.39	1619.49	1615.02	7061.7	7060.4
271	0.	1785.10	1789.61	1782.76	8846.8	8843.2
272	0.	1875.41	1886.01	1876.79	10722.2	10719.9
273	0.	1897.40	1895.89	1884.28	12619.6	12604.2
274	0.	1825.69	1818.19	1804.20	14445.3	14408.4
275	0.	1668.78	1663.90	1647.52	16114.1	16055.9
276	0.	1451.93	1453.54	1434.79	17566.0	17490.7
277	0.	1208.75	1212.79	1191.66	18774.7	18682.4
278	0.	960.32	967.41	943.90	19735.1	19626.3
279	0.	741.08	738.92	713.03	20476.1	20339.3
280	0.	548.72	541.96	513.68	21024.9	20853.0
281	0.	385.51	383.59	352.93	21410.4	21205.9
282	0.	264.27	264.30	231.26	21674.6	21437.2
283	0.	176.59	179.94	144.51	21851.2	21581.7
284	0.	120.70	123.93	86.13	21971.9	21667.8
285	0.	86.32	89.13	48.95	22058.2	21716.8
286	0.	65.16	69.10	26.53	22123.4	21743.3

Table XIII

ANALYSIS OF PLUTONIUM SOURCE P-5612 ALPHA SPECTRUM

WITH SMOOTHED INPUT DATA

```
222   PU-239 P-5612  ALPHA TOT-AREA S-D 4.42 IN.  20 DEC 67

ZERO BACKGROUND

TX =    - .        TZ =    - .        DT =   0.
THE DECAY FACTOR =    1.  00000   T1/2 =    -0.    DAYS.
THE COUNT TIME IS  40.0  MINUTES.
THE SPECTRUM HAS BEEN SMOOTHED.
THE PEAK IS EXPECTED IN CHANNEL 276.00.   (399 CHANNELS)


START PHOTOPEAK ANALYSIS.

THE PEAK APPEARS TO BE NEAR CHANNEL 278.63.
 6 ITERATIONS.


THE PEAK AMPLITUDE IS 332[illegible].95 C[illegible]/CH AT CHANNEL 278.58.
THE STANDARD DEVIATION IS  4.[illegible]7 CHANNELS, (  3.43 PERCENT FWHM).
THE PHOTOPEAK COUNT-RATE IS 33843.76 CPM AT TX, WHICH CORRESPONDS
TO A COUNT-RATE OF 3.3844E+04 CPM AT TZ.
```

I	B(I)	Y(I)	FIT	GAUSS	SUMY	SUMG
266	0.	86.03	121.93	27.75	86.0	27.7
267	0.	119.87	145.59	57.61	205.9	85.4
268	0.	178.40	194.39	112.61	384.3	198.0
269	0.	275.66	282.75	207.17	660.0	405.1
270	0.	431.24	428.15	358.78	1091.2	763.9
271	0.	658.87	648.02	584.85	1750.1	1348.8
272	0.	969.44	954.37	897.40	2719.5	2246.2
273	0.	1363.61	1346.92	1296.16	4083.1	3542.3
274	0.	1816.58	1806.75	1762.19	5899.7	5304.5
275	0.	2287.2[illegible]	2293.50	2255.14	8186.9	7559.7
276	0.	2733.20	2748.72	2716.56	10920.1	1[illegible]276.2
277	0.	3084.06	3106.25	3080.29	14004.2	13356.5
278	0.	3292.92	3307.43	3287.68	17297.1	16644.2
279	0.	3320.53	3316.58	3303.03	20617.6	19947.2
280	0.	3151.63	313[illegible].99	3123.64	23769.2	23070.8
281	0.	2804.35	2781.73	2780.58	26573.6	25851.4
282	0.	2342.30	2324.84	2329.89	28915.9	28181.3
283	0.	1823.45	1826.39	1837.64	30739.3	3[illegible]019.0
284	0.	1326.67	1346.85	1364.31	32066.0	31383.3
285	0.	900.74	929.77	953.43	32966.8	32336.7
286	0.	577.39	597.32	627.18	33544.1	32963.9
287	0.	353.87	352.29	388.35	33898.0	33352.2
288	0.	216.00	184.08	226.35	34114.0	33578.6
289	0.	133.58	75.71	124.18	34247.6	33702.8
290	0.	86.88	9.46	64.13	34334.5	33766.9
291	0.	62.25	-29.70	31.17	34396.7	33798.1

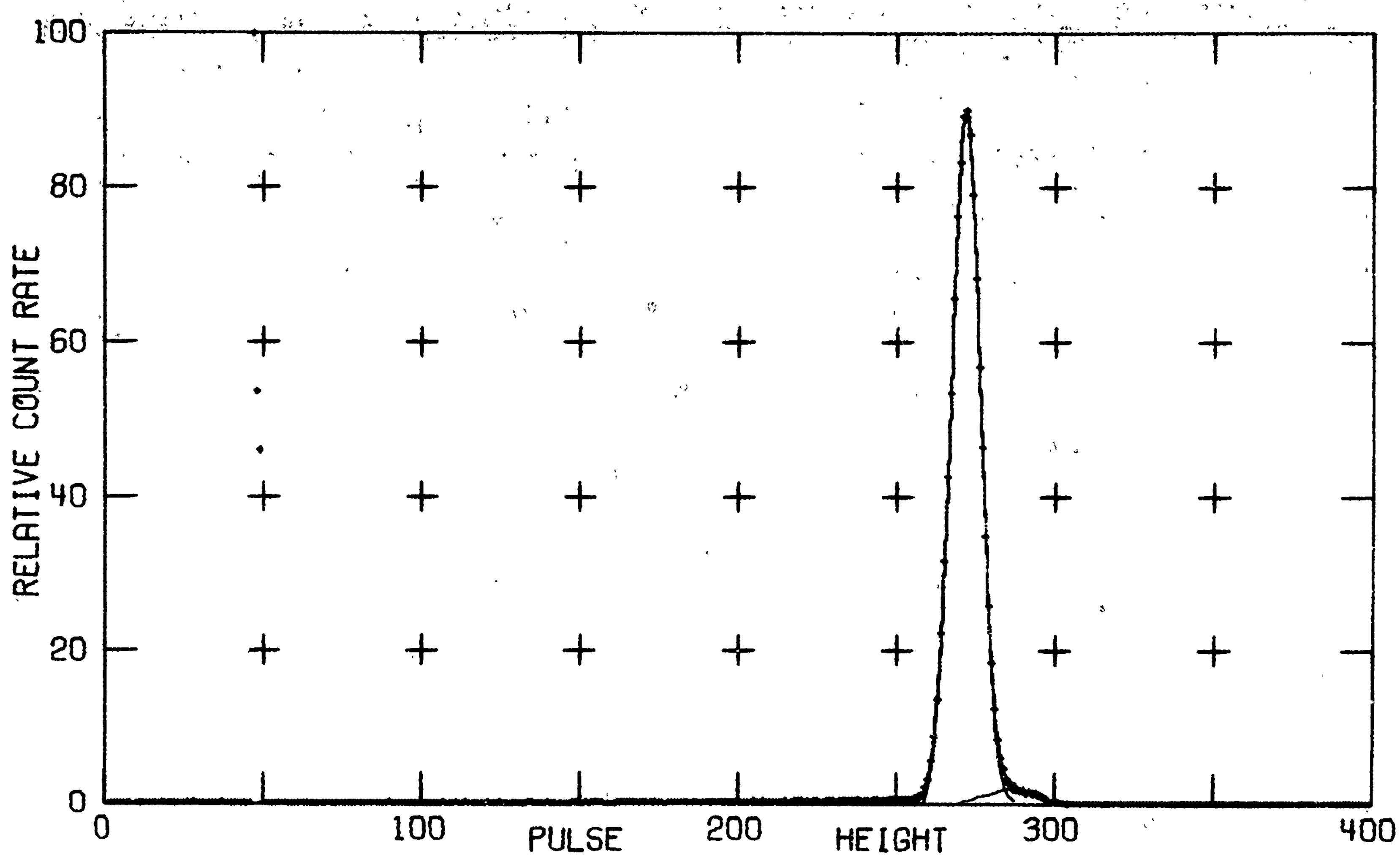


Figure 13. Plot of PPA-II Alpha Analysis of Plutonium Source P-5611 (17.4-kev/cnannel)

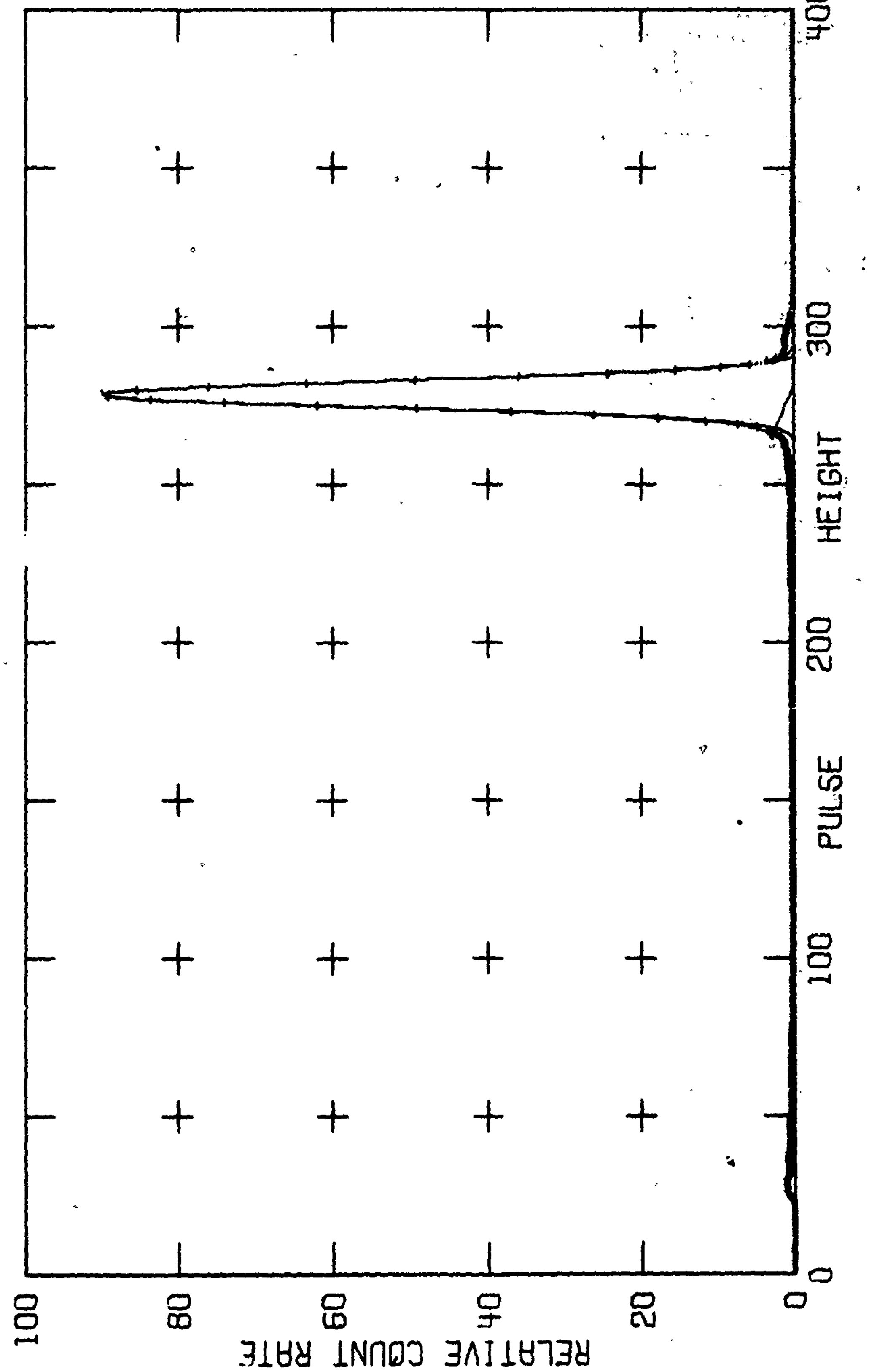


Figure 14. Plot of PPA-II Alpha Analysis of Plutonium Source P-5612 (17.4-kev/channel)

Table XIV

ANALYSIS OF Am-241 SOURCE S-307 ALPHA SPECTRUM
WITH SMOOTHED INPUT DATA

241 AM-241 S-307 ALPHA S-D 4.42 IN. 21 DEC 67

ZERO BACKGROUND

TX = -0. TZ = -0. DT = 0.
THE DECAY FACTOR = 1.00000000 T1/2 = -0. DAYS.
THE COUNT TIME IS 100.00 MINUTES.
THE SPECTRUM HAS BEEN SMOOTHED.
THE PEAK IS EXPECTED IN CHANNEL 315.00. (399 CHANNELS)

START PHOTOPEAK ANALYSIS.

THE PEAK APPEARS TO BE NEAR CHANNEL 314.87.
3 ITERATIONS.

THE PEAK AMPLITUDE IS 31.39 CPM/CH AT CHANNEL 314.82.
THE STANDARD DEVIATION IS 3.64 CHANNELS. (2.72 PERCENT FWHM).
THE PHOTOPEAK COUNT-RATE IS 286.74 CPM AT TX, WHICH CORRESPONDS
TO A COUNT-RATE OF 2.8674E+02 CPM AT TZ.

I	B(I)	Y(I)	FIT	GAUSS	SUMY	SUMG
303	0.	1.98	13.97	.16	2.0	.2
304	0.	2.78	12.86	.38	4.8	.5
305	0.	3.88	11.99	.83	8.6	1.4
306	0.	5.74	11.52	1.68	14.4	3.1
307	0.	8.34	11.66	3.15	22.7	6.2
308	0.	11.61	12.66	5.46	34.3	11.7
309	0.	15.14	14.66	8.79	49.5	20.5
310	0.	18.84	17.66	13.11	68.3	33.6
311	0.	21.95	21.37	18.14	90.3	51.7
312	0.	24.92	25.20	23.29	115.2	75.0
313	0.	27.40	28.31	27.72	142.6	102.7
314	0.	28.65	29.88	30.61	171.2	133.3
315	0.	29.04	29.29	31.35	200.3	164.7
316	0.	28.12	26.40	29.77	228.4	194.5
317	0.	22.88	21.53	26.23	251.3	220.7
318	0.	15.16	15.41	21.43	266.4	242.1
319	0.	7.41	8.90	16.24	273.9	258.4
320	0.	1.32	2.75	11.41	275.2	269.8
321	0.	-.99	-2.54	7.44	274.2	277.2
322	0.	-.30	-6.81	4.50	273.9	281.7
323	0.	-.00	-10.10	2.52	273.9	284.2
324	0.	-.01	-12.64	1.31	273.9	285.5
325	0.	.00	-14.64	.63	273.9	286.2
326	0.	-.00	-16.31	.28	273.9	286.4

APPENDIX I

COMPUTER PROGRAM E F F Y

```
      PROGRAM EFFY(INPUT,OUTPUT)
C     SOLVE FOR PHOTOPEAK EFFICIENCIES FOR FIVE ENERGIES
C
      COMMON/HEAD/JOB(12)
      DIMENSION R(30), Z(30), EP(30), T(30), G(30)
      READ 999, JOB
      READ 1, FN, RO
      N = FN + 0.5
      RO = RO*3.7E04*60.
      READ 21, (Z(I),I=1,N)
      READ 21, (T(I), I=1,N)
      SUMT = 0.0
      DO 40 I=1,N
      TIME = T(I)
40    SUMT = SUMT + TIME
      F=0.359
      ASQR=0.9549
      DO 27  J=1,5
      READ 1,E
      READ 22,(R(K), K=1,N)
      CALL PAGE (0)
      PRINT 60,E
      CALL PAGE(2)
      PRINT 23
      RO = RO*F
      DO 14 I = 1,N
      TEMZ = Z(I)
      TEMD = SQRT(ASQR+TEMZ*TEMZ)
      TEMG = .5*(1.-TEMZ/TEMD)
      TEMRD = RO*TEMG
      G(I) = TEMG
      TEMR = R(I)
      EP(I) = TEMR / TEMRD
      PRINT 18,EP(I),Z(I),TEMRD,TEMR
14    CALL PAGE (2)
      SUME = 0.
      SUMWT = 0.
C
C     COMPUTE THE MEAN EFFICIENCY
C
      DO 5 I=1,N
      TIME = T(I)
      TEMG = G(I)
      TEMR = R(I)
      WT = TIME*TEMR/TEMG
      SUMWT = SUMWT+WT
      TEMEP = EP(I)
      EFT = TEMEP * WT
```

```
5     SUME = SUME + EFT
      EPBAR = SUME/SUMWT
      CALL PAGE (2)
      PRINT 2,EPBAR
C
C     COMPUTE THE EXPERIMENTAL ERROR
C
      SUMVR = 0.
      CALL PAGE(0)
      PRINT 63
      DO 19 I=1,N
      TEMEP = EP(I)
      TIME = T(I)

      TEMG = G(I)
      TEMR = R(I)
      WT = TIME * TEMR / TEMG
      TSIG = TEMEP-EPBAR
      TVAR = TSIG*TSIG
      PRINT 61,Z(I),TVAR,G(I),TIME
      CALL PAGE(2)
      TVAR = TVAR*WT/SUMWT
19    SUMVR = SUMVR+TVAR
      SUMVR = FN/(FN-1.)*SUMVR
      SIGMA = SQRT(SUMVR)
      PRINT 62,SIGMA
      IF(J-1) 15,15,29
15    CALL PAGE(0)
C
C     COMPUTE NEW VALUES FOR DISTANCE Z(I)
C
      PRINT 12
      DO 6 I= 1,N
      TRATE =R(I)
      TEMRD = TRATE/EPBAR
      TERM = SQRT(ASQR)*(1.-2.*TEMRD/RO)/2.
      DENOM = SQRT(TEMRD/RO*(1.-TEMRD/RO))
      Z(I) = TERM/DENOM
      PRINT 13,Z(I),TEMRD,TRATE
6     CALL PAGE (2)
29    GO TO (30,31,32,33,27),J
30    F=0.375
      GO TO 27
31    F=0.512/0.375
      GO TO 27
32    F=0.138/.512
      GO TO 27
33    F=0.07/.138
27    CONTINUE
      STOP
```

```
999   FORMAT (12A6)
1     FORMAT (2F10,2)
21    FORMAT(8E10,4)
22    FORMAT(8F10,2)
23    FORMAT(5X,50H EFFICIENCY   DISTANCE (CM)   TRUE CPM    OBS, CPM)
18    FORMAT (1X/5X,F10,8,6X,F6,2, 7X,F9,2,3X,F9,2)
2     FORMAT(1X/3X,32HTHE MEAN PHOTOPEAK EFFICIENCY IS,2X,E10,4)
13    FORMAT (1X/13X,F6,2,8X,F9,2,7X,F9,2)
12    FORMAT(10X,13HDISTANCE (CM),5X,8HTRUE CPM,5X,12HOBSERVED CPM)
60    FORMAT(1X/3X,20HTHE PHOTON ENERGY IS,F6,3,4H KEV/1X)
61    FORMAT(1X/8X,E10,4,6X,E10,4,4X,E10,4,3X,F7,2)
62    FORMAT(1X/3X,35HTHE PHOTOPEAK EFFICIENCY STD,DEV,IS,2X,E10,4)
63    FORMAT(1X/6X,13HDISTANCE (CM),6X,8HVARIANCE,6X,8HQ-FACTOR,6X,4HTIM
     1E)
      END
       SUBROUTINE PAGE (N)
C
       COMMON/HEAD/JOB(12)
       DATA LINE/1/
C
       IF (N) 1,2,5
1      NP=0
       LINE=1
2      IF (LINE) 3,4,3
3      NP=NP+1
       PRINT 6, NP,JOB
       LINE=0
4      RETURN
5      LINE=LINE+N
       IF (LINE-50) 4,3,3
C
C
6      FORMAT (5H1PAGE,I4,60X,7HA L F Y/1H0,12A6/1X)
       END
```

APPENDIX II

COMPUTER PROGRAM A L F Y

```
      PROGRAM ALFY (INPUT,OUTPUT)
C
C     ALFY SOLVES A GEOMETRIC EQUATION FOR ALPHA SOURCE AND DETECTOR,
C     CORRECTS FOR THE AREA RESTRICTION AND COMPUTES A MEAN 4-PI ALPHA
C                EMISSION RATE.
C
      COMMON/HEAD/JOB(12)
      DIMENSION R(30),T(30),Z(30),G(30)
      READ 1, X
      M = X + .5
      DO 88 K=1,M
      READ 999,JOB
C
C     READ IN DISTANCES, SOURCE AND DETECTOR AREAS, AND COMPUTE THE
C                   GEOMETRY FACTORS.
C
      READ 1,FN
      N=FN+0.5
      READ 100, ASQR
      READ 100,BSQR
      READ 100, AREA
      READ 21, (Z(I),I=1,N)
      READ 21, (T(I), I=1,N)
      READ 21, (R(I),I=1,N)
      SUMT = 0.0
      SUMC = 0.0
      RTOT = 0.0
      CALL PAGE (0)
      PRINT 38
      CALL PAGE (2)
C
      SCWT =0.
      SUMWT = 0.
      DO 3 I=1,N
      TEMZ = Z(I)
      TEMD = SQRT(ASQR+TEMZ*TEMZ)
      TERM1 = 0.5*(1.-TEMZ/TEMD)
      TERM2=.1875*ASQR*BSQR*TEMZ/TEMD**5.
      TERM3=.15625*ASQR*BSQR*BSQR*TEMZ/TEMD**9.*(TEMZ*TEMZ-.75*ASQR)
      TEMG = TERM1-TERM2+TERM3
      TIME = T(I)
      SUMT = SUMT + TIME
      TEMR = R(I)
      CT = TEMR*TIME
      SUMC = SUMC + CT
      R4PI = (TEMR/TEMG) * AREA/BSQR
      WT = TIME*TEMR/TEMG
      RWT = R4PI*WT
```

```
      SUMWT = SUMWT +W1
      RTOT = RTOT + RWI
      PRINT 30, TEMR,R4PI,TEMZ,TEMG
      G(I) = TEMG
3     CALL PAGE (2)
      IF (N-1) 88,88,7
C
C     COMPUTE THE WEIGHTED MEAN 4-PI COUNTING RATE
C
7     RBAR = RTOT/SUMW1
      CALL PAGE (2)
      PRINT 39
      PRINT 31, RBAR
      CALL PAGE (2)
      ACT = RBAR/(3.7E04*60.)
      PRINT 32, ACT
C
C     COMPUTE VARIANCE OF THE CALCULATED 4-PI COUNTING RATES
C
      CALL PAGE (0)
      PRINT 35
      CALL PAGE (1)
C
      VRMS = 0.0
      VTOT = 0.0
      SUMSG = 0.
      RMSQ = 0.
      VARTH = 0.0
      SQSG = 0.0
C
      DO 4 I=1,N
      TIME = T(I)
      TEMR = R(I)
      TEMG = G(I)
      R4PI = TEMR/TEMG*AREA/BSQR
      WT = TIME*TEMR/TEMG
      TVARC = (RBAR*TEMG*BSQR/AREA-TEMR)/TEMG*AREA/BSQR
      SIGSQ = TVARC*TVARC
      TVARC=SQRT(SIGSQ)
      TVAR=TVARC*TVARC*TEMG/AREA*BSQR
      TSIG = SQRT(TEMR/TIME)/TEMG*AREA/BSQR
      PRINT33,R4PI,TVARC,TVAR,TSIG
      VARI = TEMP/TIME/TEMG*AREA/BSQR
      VARTH = VARTH+VARI
      SQSG = SQSG+TSIG*TSIG
      VTOT = VTOT+TVAR
      SUMSG=SUMSG+SIGSQ
      SIGSQ = SIGSQ*WT/SUMWT
      TVAR = TVAR*WT/SUMWT
      TVRMS = TVAR*WT/SUMWT
      VRMS = VRMS+TVRMS
      SIGSQ=SIGSQ*WT/SUMWT
      RMSQ = RMSQ+SIGSQ
4     CALL PAGE(2)
```

```
C
      Y = FN/(FN-1.)
      VRMS = Y*VRMS
      VTOT = Y*VTOT
      SUMSG = Y*SUMSG
      RMSQ = Y*RMSQ
      SIGMA = SQRT(SUMSG)
      RMSIG = SQRT(RMSQ)
      SQSG = SQSG/FN
      SIGTH = SQRT(SQSG)
      CALL PAGE (0)
      PRINT 66, VTOT
      PRINT 67, SIGMA
      PRINT 68,VRMS
      PRINT 69, RMSIG
      PRINT 70, VARTH
      PRINT 71, SIGTH
      PRINT 72,SUMT
      PRINT 73, SUMWT
      PRINT 74, SUMC
      CALL PAGE (12)
88    CONTINUE
      STOP
999   FORMAT (12A6)
1     FORMAT (F10.2)
21    FORMAT (8F10.2)
38    FORMAT(1X/3X,14HOBS. RATE(CPM),3X,15H4-PI RATE (CPM),3X,14HMEAN.DI
     1ST.(CM),3X,8HG-FACTOR//1X)
30    FORMAT(1X/3X,F10.2,8X,F12.2,8X,F10.2,5X,E10.4)
39    FORMAT(1X/)
35    FORMAT(3X,21H4-PI COUNT RATE (CPM),3X,9HSIGMA-EXP,10X,8HVARIANCE,1
     10X,5HSIGMA//1X)
31    FORMAT(4X,36HTHE WEIGHTED MEAN 4-PI COUNT RATE IS,F12.2,4H CPM,1X)
32    FORMAT(3X,21HTHE ALPHA ACTIVITY IS,F10.4,1X,12HMICROCURIES.)
33    FORMAT(7X,E10.4,9X,E10.4,8X,E10.4,8X,E10.4/1X)
66    FORMAT(3X,29HTHE MEAN SQUARE DISPERSION IS,3X,E10.4/1X)
67    FORMAT(3X,30HTHE MEAN STANDARD DEVIATION IS,3X,E10.4/1X)
68    FORMAT(3X,21HTHE RMS DISPERSION IS,3X,E10.4/1X)
69    FORMAT(3X,29HTHE RMS STANDARD DEVIATION IS,3X,E10.4/1X)
70    FORMAT(1X/3X,29HTHE THEORETICAL DISPERSION IS,F12.0)
71    FORMAT(1X/3X,27HTHE THEORETICALSTD. DEV. IS,F12.4)
72    FORMAT(1X/3X,27HTHE TOTAL COUNTING TIME WAS,F10.2,2X,4HMINS)
73    FORMAT(1X/3X,22HTHE TOTAL WT FACTOR IS,2X,E10.4)
74    FORMAT(1X/3X,36HTHE TOTAL NO. OF COUNTS OBSERVED WAS,2X,E10.4)
100   FORMAT(F10.5)
      END
```

APPENDIX III

COMPUTER PROGRAM P L U T O

```
      PROGRAM PLUTO(INPUT,OUTPUT)
C
C     PROGRAM PLUTO USES KNOWN INTRINSIC PHOTOPEAK EFFICIENCIES FOR A
C     DETECTOR TO DETERMINE SOURCE-DETECTOR GEOMETRY AND 4-PI COUNTING
C     RATES AT VARIOUS ENERGIES IN A COMPLEX SPECTRUM
C
C     ON THE FIRST PASS, PLUTO PROCESSES THE MOST SIGNIFICANT DATA, REP-
C     RESENTED BY THE PHOTOPEAK INTEGRAL CONTAINING THE GREATEST NO.
C     OF COUNTS OR HIGHEST COUNT RATE.  FROM THIS DATA, PLUTO COMPUTES
C     THE GEOMETRY FACTOR FOR A POINT-SOURCE, OR CIRCULAR SOURCE AND
C     CIRCULAR DETECTOR, COMPUTES  A MEAN 4-PI COUNT RATE, WEIGHTED WITH
C     THE TOTAL NO. OF COUNTS OBSERVED AND THE INDIVIDUAL GEOMETRY
C     FACTORS FOR EACH MEASUREMENT.  FROM THE MEAN RATE, NEW GEOMETRY
C     FACTORS ARE COMPUTED FOR EACH MEASUREMENT AND THESE ARE THEN USED
C     FOR COMPUTING THE MEAN RATES OF OTHER PHOTOPEAK INTEGRALS IN THE
C     SAME SPECTRUM.
C     PLUTO WAS WRITTEN BY CAPT. NEIL A. CODDINGTON FOR USE IN AN AFIT
C     MASTER≠S DEGREE THESIS AT THE AIR FORCE WEAPONS LABORATORY ON
C                          DEC 10, 1967
C
      COMMON/HEAD/JOB(12)
      DIMENSION  Z(30), T(30), G(30), R(30),C(30)
      READ 1,X
      MM = X +.5
      DO 50 J=1,MM
      READ 999,JOB
      READ 1,FN
      N=FN+0.5
C
      READ 1,E
      READ 500, EPBAR
      READ 777, BSQR
      READ 21, (Z(I),I=1,N)
      READ 21,(T(I), I=1,N)
      READ 21, (R(I),I=1,N)
      SUMT = 0.0
C
      DO 40 I=1,N
      TIME = T(I)
40    SUMT = SUMT + TIME
C
C     SOLVE FOR INITIAL VALUES OF GEOMETRY FACTORS
C     AND INITIAL VALUES OF 4-PI COUNT RATES
C
      ASQR = 0.9549
      SUMWT = 0.
      RTOT = 0.
```

```
      CALL PAGE (0)
      PRINT 35,E
      PRINT 30
      CALL PAGE (6)
C
      DO 3 I=1,N
      TEMZ = Z(I)
      TEMD = SQRT(ASQR+TEMZ*TEMZ)
      TERM1 = 0.5*(1.-TEMZ/TEMD)
      TERM2=.1875*ASQR*BSQR*TEMZ/TEMD**5.
      TERM3=.15625*ASQR*BSQR*BSQR*TEMZ/TEMD**9.*(TEMZ*TEMZ-.75*ASQR)
      TEMG = TERM1-TERM2+TERM3
      TIME = T(I)
      TEMR =R(I)
      R4PI=TEMR/(EPBAR*TEMG)
      WT = TIME*TEMR/TEMG
      SUMWT = SUMWT + WT
      RWT = R4PI*WT
      RTOT = RTOT + RWT
      PRINT 37, TEMR, R4PI,TEMZ,TEMG
      G(I) = TEMG
3     CALL PAGE(2)
C
C     COMPUTE THE WEIGHTED MEAN 4-PI COUNTING RATE
C
      EFFY = EPBAR
      M=0
      L=4
      K=0
C
45    RBAR = RTOT/SUMWT
      PRINT 31, RBAR
C
      CALL PAGE (0)
      PRINT 35,E
      PRINT 32
      CALL PAGE (6)
C
      VTOT = 0.0
      VRMS = 0.0
      SUMSG = 0.
      RMSQ = 0.
      SUMC = 0.
      VARTH = 0.
      SQSG = 0.
C
C     COMPUTE THE VARIANCE OF THE CALCULATED 4-PI COUNTING RATES
C
      DO 4 I=1,N
      TIME = T(I)
      TEMR = R(I)
      TEMG = G(I)
      CT = TEMR*TIME
      SUMC = SUMC + CT
      R4PI = TEMR/(EFFY*TEMG)
```

```
      WT = TIME*TEMR/TEMG
      TVARC = RBAR*R4PI
      SIGSQ = TVARC*TVARC
      TVARC = SQRT(SIGSQ)
      TVAR = TVARC*TVARC*TEMG*EFFY
      TSIG = SQRT(TEMR/TIME)/EFFY/TEMG
      PRINT33,R4PI,TVARC,TVAR,TSIG
      VARI = TEMR/TIME/EFFY/TEMG
      VARTH = VARTH+VARI
      SQSG = SQSG+TSIG*TSIG
      VTOT = TVAR + VTOT
      SUMSG = SUMSG+SIGSQ
      TVRMS = TVAR*WT/SUMWT
      VRMS= VRMS+TVRMS
      SIGSQ = SIGSQ*WT/SUMWT
      RMSQ = RMSQ+SIGSQ
4     CALL PAGE(2)
C
      CALL PAGE(0)
      Y = FN/(FN-1.)

      VRMS = Y*VRMS
      SUMSG = Y*SUMSG
      SIGSQ = Y*VTOT
      RMSQ = Y*RMSQ
      SIGMA = SQRT(SUMSG)
      RMSIG = SQRT(RMSQ)
      SQSG = SQSG/FN
      SIGTH = SQRT(SQSG)
      CALL PAGE(2)
      PRINT 66, SIGSQ
      CALL PAGE(2)
      PRINT 67,SIGMA
      CALL PAGE(2)
      PRINT 68,VRMS
      CALL PAGE(2)
      PRINT 69, RMSIG
      CALL PAGE(2)
      PRINT 71, VARTH
      CALL PAGE(2)
      PRINT 70, SIGTH
      CALL PAGE(2)
      PRINT 72,SUMT
      CALL PAGE(2)
      PRINT 73, SUMWT
      CALL PAGE(2)
      PRINT 74, SUMC
      IF (K) 47,47,48
48    IF (L) 50,50,49
49     L=L-1
47    K=K+1
      IF(M) 9,9,46
```

```
C     BACKSOLVE FOR GEOMETRIC FACTORS, USING THE MEAN 4-PI RATE,THE
C     OBSERVED RATES, AND THE KNOWN PHOTOPEAK EFFICIENCY,
C
9     M=M+1
      DO 7 I=1,N
      ROBS=R(I)
      TEMRD = ROBS/EPBAR
7     G(I) = TEMRD/RBAR
      IF (K-1) 52,52,46
C
C     READ NEW VALUES OF ENERGY, EFFICIENCY, AND OBSERVED COUNT RATES.
C
46    READ 1, E
      READ 500,EFFY
      READ 21, (R(I),I=1,N)
C
52    CALL PAGE (0)
      PRINT 35,E
      PRINT 38
      CALL PAGE (6)
C
C     COMPUTE THE NEXT VALUES FOR MEAN COUNT RATE AND ERRORS
C
      SUMWT = 0.
      RTOT = 0.
C
      DO 14 I=1,N
      TEMR = R(I)
      TEMG = G(I)
      R4PI = TEMR/(EFFY*TEMG)
      TIME = T(I)
      WT = TIME*TEMR/TEMG
      RWT = R4PI*WT
      RTOT = RTOT + RWT
      SUMWT = SUMWT + WT
      PRINT36,R(I),R4PI,EFFY,Z(I),G(I)
14    CALL PAGE (2)
C
      GO TO 45
50    CONTINUE
      STOP
999   FORMAT (12A6)
1     FORMAT (F10.2)
21    FORMAT (8F10.2)
```

```
30    FORMAT(1X/3X,14HOBS. RATE(CPM),3X,15H4-PI RATE (CPM),3X,14HMEAS.DI
     1ST.(CM),3X,8HG-FACTOR//1X)
37    FORMAT(3X,F10.2,8X,F10.2,8X,F10.2,5X,E10.4/1X)
31    FORMAT(4X,36HTHE WEIGHTED MEAN 4-PI COUNT RATE IS,F12.2,5H CPM.)
32    FORMAT(3X,21H4-PI COUNT RATE (CPM),3X,9HSIGMA-EXP,10X,8HVARIANCE,1
     10X,5HSIGMA//1X)
33    FORMAT(7X,F10.2,9X,E10.4,7X,E10.4,8X,E10.4/1X)
35    FORMAT(5X,20HTHE PHOTON ENERGY IS,F7.3,5H KEV.//1X)
38    FORMAT(2X,13HOBS.RATE(CPM),2X,14H4-PI RATE(CPM),5X,4HEFF.,6X,5HDIS
     1T.,5X,8HG-FACTOR//1X)
36    FORMAT(5X,F10.2,4X,F10.2,5X,F6.4,1X,F10.2,5X,E10.4/1X)
66    FORMAT(1X/3X,29HTHE MEAN SQUARE DISPERSION IS,3X,E10.4)
67    FORMAT(1X/3X,30HTHE MEAN STANDARD DEVIATION IS,3X,E10.4)
68    FORMAT(1X/3X,21HTHE WTD DISPERSION IS,3X,E10.4)
69    FORMAT(1X/3X,29HTHE WTD STANDARD DEVIATION IS,3X,E10.4)
70    FORMAT(1X/3X,28HTHE THEORETICAL STD. DEV. IS,3X,E10.4)
71    FORMAT(1X/3X,27HTHE THEORETICAL VARIANCE IS,3X,E10.4)
72    FORMAT(1X/3X,27HTHE TOTAL COUNTING TIME WAS,F10.2,2X,4HMINS)
73    FORMAT(1X/3X,22HTHE TOTAL WT FACTOR IS,2X,E10.4)
74    FORMAT(1X/3X,36HTHE TOTAL NO. OF COUNTS OBSERVED WAS,2X,E10.4)
500   FORMAT(F10.8)
777   FORMAT (F10.5)
      END
```

APPENDIX IV

TABULATED RESULTS OF COMPUTER PROGRAM EFFY

TMC - GE(LI) DETECTOR PHOTOEFFICIENCY FOR IAEA AM-241 STANDARD

THE PHOTON ENERGY IS59.543 KEV

EFFICIENCY	DISTANCE (CM)	TRUE CPM	OBS. CPM
.52426244	8.02	32004.49	16778.75
.55066983	10.56	18546.27	10212.87
.63549050	15.64	8484.38	5391.74
.61533341	18.20	6270.21	3858.27
.59277436	18.20	6270.21	3716.82
.63176776	20.74	4830.84	3051.97
.63321937	23.28	3835.51	2428.72
.67021736	27.53	2743.72	1838.89
.57069537	25.82	3118.77	1779.87
.57571157	33.44	1860.17	1070.92
.61047188	33.44	1860.17	1135.58
.63707163	33.44	1860.17	1185.06
.61059622	38.52	1402.10	856.12
.61525609	41.06	1234.07	759.27
.56381661	41.06	1234.07	695.79
.59686428	48.68	878.07	524.09
.60386692	66.46	471.16	284.52
.62914477	66.46	471.16	296.43

THE MEAN PHOTOPEAK EFFICIENCY IS 6.0796E-01

THE PHOTOPEAK EFFICIENCY STD.DEV.IS 5.2404E-02

TMC - GE(LI) DETECTOR PHOTOEFFICIENCY FOR IAEA AM-241 STANDARD

THE PHOTON ENERGY IS13.900 KEV

EFFICIENCY	DISTANCE (CM)	TRUE CPM	OBS. CPM
.29612358	8.62	10414.60	3084.01
.30034324	11.08	6323.66	1899.27
.31406165	15.28	3332.47	1046.60
.31654385	18.08	2383.30	754.42
.31961328	18.42	2295.81	733.77
.29818486	20.33	1884.67	561.98
.31054820	22.80	1499.45	465.65
.32299207	26.21	1135.04	366.61
.30098603	26.64	1098.59	330.66
.29812625	34.36	660.83	197.01
.30447642	33.36	700.74	213.36
.31836861	32.66	731.29	232.82
.32930167	38.43	528.24	173.95
.30279807	40.81	468.46	141.85
.29029527	42.63	429.29	124.62
.30501250	49.13	323.33	98.62
.25524836	66.68	175.52	44.80
.29202155	65.33	182.86	53.40

THE MEAN PHOTOPEAK EFFICIENCY IS 3.0623E-01

THE PHOTOPEAK EFFICIENCY STD.DEV.IS 4.7181E-02

TMC - GE(LI) DETECTOR PHOTOEFFICIENCY FOR IAEA AM-241 STANDARD

THE PHOTON ENERGY IS17.800 KEV

EFFICIENCY	DISTANCE (CM)	TRUE CPM	OBS. CPM
.46727898	8.62	14219.41	6644.43
.45558267	11.06	8633.91	3933.46
.42261769	15.28	4549.93	1922.88
.43068793	18.08	3254.00	1401.46
.42666866	18.42	3134.54	1337.41
.41466228	20.33	2573.20	1067.01
.41875840	22.80	2047.24	857.30
.43040887	26.21	1549.71	667.01
.43267718	26.64	1499.94	648.99
.42404004	34.36	902.25	382.59
.43252722	33.36	956.75	413.82
.42125060	32.66	998.46	420.60
.43133714	38.43	721.22	311.09
.42319569	40.81	639.61	270.68
.42375287	42.63	586.12	248.37
.41879731	49.13	441.45	184.88
.42401646	66.68	239.64	101.61
.40449516	65.33	249.67	100.99

THE MEAN PHOTOPEAK EFFICIENCY IS 4.2464E-01

THE PHOTOPEAK EFFICIENCY STD.DEV.IS 2.0097E-02

TMC - GE(LI) DETECTOR PHOTOEFFICIENCY FOR IAEA AM-241 STANDARD

THE PHOTON ENERGY IS20.900 KEV

EFFICIENCY	DISTANCE (CM)	TRUE CPM	OBS. CPM
.45561280	8.62	3832.57	1746.17
.47571478	11.08	2327.11	1107.04
.45726834	15.28	1226.35	560.77
.45979981	18.08	877.06	403.27
.48530135	18.42	844.86	410.01
.49816996	20.33	693.56	345.51
.52483180	22.80	551.80	289.60
.45346382	26.21	417.70	189.41
.45651436	26.64	404.28	184.56
.44176337	34.36	243.18	107.43
.52044844	33.36	257.87	134.21
.44352790	32.66	269.11	119.36
.42275409	38.43	194.39	82.18
.45651040	40.81	172.39	78.70
.45550752	42.63	157.98	71.96
.48602433	49.13	118.99	57.83
.42282323	66.68	64.59	27.31
.41876157	65.33	67.29	28.18

THE MEAN PHOTOPEAK EFFICIENCY IS 4.5384E-01

THE PHOTOPEAK EFFICIENCY STD.DEV.IS 3.9333E-02

TMC - GE(LI) DETECTOR PHOTOEFFICIENCY FOR IAEA AM-241 STANDARD

THE PHOTON ENERGY IS26.348 KEV

EFFICIENCY	DISTANCE (CM)	TRUE CPM	OBS. CPM
.45680700	6.62	1944.06	888.06
.47846633	11.08	1180.42	564.79
.48095004	15.28	622.06	299.18
.48055301	18.08	444.88	213.79
.48048024	18.42	428.55	205.91
.48669003	20.33	351.81	171.22
.51708411	22.80	279.90	144.73
.49415986	26.21	211.87	104.70
.46715760	26.64	205.07	95.80
.51234471	34.36	123.35	63.20
.48568282	33.36	130.81	63.53
.49916636	32.66	136.51	68.14
.50352609	38.43	98.60	49.65
.43123452	40.81	87.45	37.71
.49205338	42.63	80.13	39.43
.51462078	49.13	60.36	31.06
.44074295	66.68	32.76	14.44
.44998506	65.33	34.13	15.36

THE MEAN PHOTOPEAK EFFICIENCY IS 4.8542E-01

THE PHOTOPEAK EFFICIENCY STD.DEV.IS 3.6527E-02

APPENDIX V

TABULATED RESULTS OF COMPUTER PROGRAM ALFY

PU-239 SOURCE P-5611 ,25 DIA DET AREA

OBS, RATE(CPM)	4-PI RATE (CPM)	MEAS,DIST,(CM)	G-FACTOR
5946,49	30910882,71	11,23	1,9238E-04
7538,75	31133396,16	9,96	2,4214E-04
5951,62	30937549,34	11,23	1,9238E-04

THE WEIGHTED MEAN 4-PI COUNT RATE IS 30967859,95 CPM

THE ALPHA ACTIVITY IS 13.9495 MICROCURIES,

THE RMS STANDARD DEVIATION IS 1.0603E+05

THE TOTAL COUNTING TIME WAS 47,51 MINS

THE TOTAL WT FACTOR IS 1,4713E+09

THE TOTAL NO, OF COUNTS OBSERVED WAS 2,9853E+05

PU-239 SOURCE P-5611 TOTAL AREA EXPOSED 21 DEC 67

OBS, RATE(CPM)	4-PI RATE (CPM)	MEAS,DIST,(CM)	G-FACTOR
21670,75	32473817,62	11,23	6,6733E-04
21383,59	32043505,73	11,23	6,6733E-04
21632,22	32416080,06	11,23	6,6733E-04
21780,27	32637934,35	11,23	6,6733E-04

THE WEIGHTED MEAN 4-PI COUNT RATE IS 32330913,57 CPM

THE ALPHA ACTIVITY IS 14.5635 MICROCURIES,

THE RMS STANDARD DEVIATION IS 2.3303E+05

THE TOTAL COUNTING TIME WAS 125.94 MINS

THE TOTAL WT FACTOR IS 4,0716E+09

THE TOTAL NO, OF COUNTS OBSERVED WAS 2,7171E+06

PU-239 SOURCE P-5612 ,25 IN DIA DET AREA TOT AREA EXPOSED 20 DEC

OBS, RATE(CPM)	4-PI RATE (CPM)	MEAS,DIST,(CM)	G-FACTOR
9263,79	48154781,41	11,23	1,9238E-04
11498,10	47484649,63	9,96	2,4214E-04
9414,78	48939653,53	11,23	1,9238E-04
9417,02	48951297,44	11,23	1,9238E-04

THE WEIGHTED MEAN 4-PI COUNT RATE IS 48305361,27 CPM

THE ALPHA ACTIVITY IS 21,7592 MICROCURIES.

THE RMS STANDARD DEVIATION IS 5,8802E+05

THE TOTAL COUNTING TIME WAS 61,14 MINS

THE TOTAL WT FACTOR IS 2,9531E+09

THE TOTAL NO, OF COUNTS OBSERVED WAS 5,9256E+05

PU-239 SOURCE P-5612   TOTAL AREA EXPOSED   20 DEC 67

OBS. RATE(CPM)	4-PI RATE (CPM)	MEAS.DIST.(CM)	G-FACTOR
33843.76	50715184.75	11.23	6.6733E-04
33917.54	50825744.75	11.23	6.6733E-04

THE WEIGHTED MEAN 4-PI COUNT RATE IS 50770524.94 CPM

THE ALPHA ACTIVITY IS 22.8696 MICROCURIES.

THE RMS STANDARD DEVIATION IS 7.8178E+04

THE TOTAL COUNTING TIME WAS 80.00 MINS

THE TOTAL WT FACTOR IS 4.0616E+09

THE TOTAL NO. OF COUNTS OBSERVED WAS 2.7105E+06

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APPENDIX VI

TABULATED RESULTS FOR COMPUTER PROGRAM PLUTO

PU-239 LX-RAY AND GAMMA RAY INTENSITIES FOR SOURCE P-5612

THE PHOTON ENERGY IS 17,030 KEV,

OBS, RATE(CPM)	4-PI RATE (CPM)	MEAS,DIST,(CM)	G-FACTOR
9909,33	1298886,96	2,94	1,9129E-02
9159,62	1200617,10	2,94	1,9129E-02
3667,53	1357356,00	5,48	6,7747E-03
1924,09	1409320,52	8,02	3,4232E-03
711,64	1323853,24	13,10	1,3478E-03
709,61	1320076,86	13,10	1,3478E-03
366,06	1292001,79	18,18	7,1040E-04
360,92	1273860,26	18,18	7,1040E-04
224,78	1290377,21	23,26	4,3677E-04
176,20	1409802,71	27,50	3,1337E-04
105,42	1242802,84	33,42	2,1268E-04
72,22	1281785,41	41,04	1,4127E-04
59,52	1242444,00	54,66	7,9754E-05
39,57	1202568,47	53,74	8,2503E-05
143,52	1219031,20	28,34	2,9520E-04
52,41	1048504,73	43,58	1,2533E-04
171,20	1206867,10	25,80	3,5568E-04
262,11	1197134,94	20,72	5,4898E-04
119,46	1203401,17	30,88	2,4890E-04
1078,93	1325791,59	10,56	2,0405E-03
54,75	1095318,33	43,58	1,2533E-04

THE WEIGHTED MEAN 4-PI COUNT RATE IS 1220839,97 CPM,

PU-239 LX-RAY AND GAMMA RAY INTENSITIES FOR SOURCE P-5612

THE PHOTON ENERGY IS 13,510 KEV,

OBS,RATE(CPM)	4-PI RATE(CPM)	EFF,	DIST,	G-FACTOR
5723,66	953806,40	,2949	2,94	2,0352E-02
5370,84	968267,72	,2949	2,94	1,8812E-02
2160,54	972790,53	,2949	5,48	7,5323E-03
1145,35	982977,40	,2949	8,02	3,9517E-03
417,74	969340,61	,2949	13,10	1,4616E-03
418,94	974906,12	,2949	13,10	1,4574E-03
218,24	984493,32	,2949	18,18	7,5181E-04
219,10	1002448,63	,2949	18,18	7,4125E-04
129,81	953632,80	,2949	23,26	4,6165E-04
107,55	1007941,22	,2949	27,50	3,6188E-04
63,65	997025,10	,2949	33,42	2,1651E-04
39,98	914146,93	,2949	41,04	1,4832E-04
21,81	911316,91	,2949	54,66	8,1165E-05
21,95	916007,80	,2949	53,74	8,1268E-05
84,15	968216,30	,2949	28,34	2,9476E-04
29,72	956408,49	,2949	43,58	1,0764E-04
101,81	982013,31	,2949	25,80	3,5161E-04
158,37	997746,06	,2949	20,72	5,3832E-04
69,64	962646,75	,2949	30,88	2,4534E-04
644,03	985697,21	,2949	10,56	2,2159E-03
34,27	1053619,46	,2949	43,58	1,1244E-04

THE WEIGHTED MEAN 4-PI COUNT RATE IS 969612,43 CPM,

PU-239 LX-RAY AND GAMMA RAY INTENSITIES FOR SOURCE P-5612

THE PHOTON ENERGY IS 20,163 KEV,

OBS,RATE(CPM)	4-PI RATE(CPM)	EFF,	DIST,	G-FACTOR
2389,43	263423,15	,4457	2,94	2,0352E-02
2245,98	267875,10	,4457	2,94	1,8812E-02
913,49	272103,45	,4457	5,48	7,5323E-03
485,80	275826,54	,4457	8,02	3,9517E-03
175,92	270059,08	,4457	13,10	1,4616E-03
177,29	272940,79	,4457	13,10	1,4574E-03
97,67	291482,74	,4457	18,18	7,5181E-04
84,53	255860,85	,4457	18,18	7,4125E-04
57,27	278338,60	,4457	23,26	4,6165E-04
45,93	284770,15	,4457	27,50	3,6188E-04
26,31	272647,65	,4457	33,42	2,1651E-04
19,94	301627,96	,4457	41,04	1,4832E-04
9,21	254593,09	,4457	54,66	8,1165E-05
10,71	295683,67	,4457	53,74	8,1268E-05
37,56	285901,93	,4457	28,34	2,9476E-04
12,62	263056,55	,4457	43,58	1,0764E-04
42,67	272284,43	,4457	25,80	3,5161E-04
64,66	269498,30	,4457	20,72	5,3832E-04
28,53	260905,47	,4457	30,88	2,4534E-04
267,40	270752,24	,4457	10,56	2,2159E-03
14,34	286133,66	,4457	43,58	1,1244E-04

THE WEIGHTED MEAN 4-PI COUNT RATE IS 273928,19 CPM,

PU-239 LX-RAY AND GAMMA RAY INTENSITIES FOR SOURCE P-5612

THE PHOTON ENERGY IS 51,560 KEV,

OBS,RATE(CPM)	4-PI RATE(CPM)	EFF,	DIST,	G-FACTOR
145,56	12363,49	,5785	2,94	2,0352E-02
133,76	12291,14	,5785	2,94	1,8812E-02
58,68	13466,65	,5785	5,48	7,5323E-03
29,13	12742,61	,5785	8,02	3,9517E-03
10,34	12229,35	,5785	13,10	1,4616E-03
10,77	12774,36	,5785	13,10	1,4574E-03
5,83	13404,77	,5785	18,18	7,5181E-04
5,43	12662,87	,5785	18,18	7,4125E-04
2,97	11120,95	,5785	23,26	4,6165E-04
3,41	16288,90	,5785	27,50	3,6188E-04
1,63	13013,91	,5785	33,42	2,1651E-04
1,09	12703,17	,5785	41,04	1,4832E-04
,71	15121,14	,5785	54,66	8,1165E-05
,73	15527,45	,5785	53,74	8,1268E-05
1,92	11259,83	,5785	28,34	2,9476E-04
,81	13008,11	,5785	43,58	1,0764E-04
2,30	11307,52	,5785	25,80	3,5161E-04
3,43	11014,22	,5785	20,72	5,3832E-04
2,22	15641,33	,5785	30,88	2,4534E-04
15,97	12458,19	,5785	10,56	2,2159E-03
1,25	19216,27	,5785	43,58	1,1244E-04

THE WEIGHTED MEAN 4-PI COUNT RATE IS 14378,49 CPM,

PU-239 LX-RAY AND GAMMA RAY INTENSITIES FOR SOURCE P-5612

THE PHOTON ENERGY IS 59,543 KEV,

OBS,RATE(CPM)	4-PI RATE(CPM)	EFF,	DIST,	G-FACTOR
1106,20	89404,82	,6080	2,94	2,0352E-02
1021,19	89289,55	,6080	2,94	1,8812E-02
415,50	90733,76	,6080	5,48	7,5323E-03
211,52	88043,56	,6080	8,02	3,9517E-03
81,60	91833,55	,6080	13,10	1,4616E-03
77,51	87480,16	,6080	13,10	1,4574E-03
42,52	93027,75	,6080	18,18	7,5181E-04
42,02	93243,09	,6080	18,18	7,4125E-04
25,39	90464,17	,6080	23,26	4,6165E-04
20,29	92224,79	,6080	27,50	3,6188E-04
14,59	110841,87	,6080	33,42	2,1651E-04
9,02	100027,77	,6080	41,04	1,4832E-04
5,99	121389,59	,6080	54,66	8,1165E-05
5,45	110306,73	,6080	53,74	8,1268E-05
18,37	102510,48	,6080	28,34	2,9476E-04
12,82	195904,95	,6080	43,58	1,0764E-04
26,72	124998,34	,6080	25,80	3,5161E-04
36,27	110824,43	,6080	20,72	5,3832E-04
14,50	97211,37	,6080	30,88	2,4534E-04
119,48	88689,76	,6080	10,56	2,2159E-03
7,04	102981,71	,6080	43,58	1,1244E-04

THE WEIGHTED MEAN 4-PI COUNT RATE IS 130510,47 CPM,

13.51-kev

THE WTD STANDARD DEVIATION IS 3,7195E+04
THE TOTAL COUNTING TIME WAS 9775.26 MINS

THE TOTAL WT FACTOR IS 2,7908E+09

THE TOTAL NO, OF COUNTS OBSERVED WAS 1,9328E+06

20.16-kev

THE WTD STANDARD DEVIATION IS 1,2895E+04
THE TOTAL COUNTING TIME WAS 9775,26 MINS

THE TOTAL WT FACTOR IS 1,1910E+09

THE TOTAL NO, OF COUNTS OBSERVED WAS 8,1111E+05

51.56-kev

THE WTD STANDARD DEVIATION IS 2,5994E+03
THE TOTAL COUNTING TIME WAS 9775,26 MINS

THE TOTAL WT FACTOR IS 7,8925E+07

THE TOTAL NO, OF COUNTS OBSERVED WAS 4,9704E+04

59.54-kev

THE WTD STANDARD DEVIATION IS 4,2651E+04
THE TOTAL COUNTING TIME WAS 9775.26 MINS

THE TOTAL WT FACTOR IS 7,1114E+08

THE TOTAL NO, OF COUNTS OBSERVED WAS 3,9470E+05

PU-239 LX-RAY AND GAMMA RAY INTENSITIES FOR SOURCE P-5611

THE PHOTON ENERGY IS 17,030 KEV,

OBS, RATE(CPM)	4-PI RATE (CPM)	MEAS,DIST,(CM)	G-FACTOR
1219,68	895428,97	8,03	3,4153E-03
1252,10	919230,14	8,03	3,4153E-03
232,94	823047,17	18,19	7,0963E-04
5938,20	778362,47	2,94	1,9129E-02
182,05	832269,51	20,73	5,4845E-04
37,97	759620,77	43,58	1,2533E-04
112,91	796566,28	25,81	3,5540E-04
1134,42	832835,28	8,03	3,4153E-03
9918,82	709080,47	2,11	3,5073E-02
349,99	780411,03	14,38	1,1245E-03
523,33	800755,67	11,84	1,6387E-03
253,16	775919,02	16,92	8,1807E-04
673,93	829623,42	10,57	2,0368E-03

THE WEIGHTED MEAN 4-PI COUNT RATE IS 795429,31 CPM,

THE TOTAL COUNTING TIME WAS 4633,18 MINS

THE TOTAL WT FACTOR IS 1,4678E+09

THE TOTAL NO, OF COUNTS OBSERVED WAS 2,3239E+06

PU-239 LX-RAY AND GAMMA RAY INTENSITIES FOR SOURCE P-5611

THE PHOTON ENERGY IS 13,510 KEV,

OBS,RATE(CPM)	4-PI RATE(CPM)	EFF,	DIST,	G-FACTOR
744,69	656905,90	,2949	8,03	3,8446E-03
763,91	656412,32	,2949	8,03	3,9468E-03
135,52	625940,23	,2949	18,19	7,3427E-04
3463,40	627511,05	,2949	2,94	1,8718E-02
104,91	620011,51	,2949	20,73	5,7385E-04
24,25	687139,15	,2949	43,58	1,1969E-04
66,48	633478,89	,2949	25,81	3,5591E-04
698,18	662166,30	,2949	8,03	3,5759E-03
5603,78	607847,47	,2949	2,11	3,1266E-02
206,05	633418,19	,2949	14,38	1,1032E-03
311,59	640591,87	,2949	11,84	1,6496E-03
150,36	639014,59	,2949	16,92	7,9801E-04
394,46	629740,65	,2949	10,57	2,1243E-03

THE WEIGHTED MEAN 4-PI COUNT RATE IS 646216,66 CPM,

THE WTD STANDARD DEVIATION IS 2,2364E+04

THE TOTAL COUNTING TIME WAS 4633,18 MINS

THE TOTAL WT FACTOR IS 6,8186E+08

THE TOTAL NO, OF COUNTS OBSERVED WAS 1,3651E+06

PU-239 LX-RAY AND GAMMA RAY INTENSITIES FOR SOURCE P-5611

THE PHOTON ENERGY IS 20,163 KEV,

OBS,RATE(CPM)	4-PI RATE(CPM)	EFF,	DIST,	G-FACTOR
302,50	176533,14	,4457	8,03	3,8446E-03
327,22	186014,84	,4457	8,03	3,9468E-03
52,15	159351,82	,4457	18,19	7,3427E-04
1508,99	180874,90	,4457	2,94	1,8718E-02
41,91	163860,30	,4457	20,73	5,7385E-04
9,15	171524,94	,4457	43,58	1,1969E-04
29,63	186786,73	,4457	25,81	3,5591E-04
276,49	173481,16	,4457	8,03	3,5759E-03
2374,60	170403,00	,4457	2,11	3,1266E-02
84,37	171584,95	,4457	14,38	1,1032E-03
130,55	177561,18	,4457	11,84	1,6496E-03
61,89	174009,18	,4457	16,92	7,9801E-04
168,72	178196,25	,4457	10,57	2,1243E-03

THE WEIGHTED MEAN 4-PI COUNT RATE IS 175513,72 CPM,

THE WTD STANDARD DEVIATION IS 5,2753E+03

THE TOTAL COUNTING TIME WAS 4633,18 MINS

THE TOTAL WT FACTOR IS 3,6213E+08

THE TOTAL NO, OF COUNTS OBSERVED WAS 5,7481E+05

PU-239 LX-RAY AND GAMMA RAY INTENSITIES FOR SOURCE P-5611

THE PHOTON ENERGY IS 21,600 KEV,

OBS,RATE(CPM)	4-PI RATE(CPM)	EFF,	DIST,	G-FACTOR
16,15	7261,27	,5785	8,03	3,8446E-03
20,33	8903,98	,5785	8,03	3,9468E-03
4,78	11253,04	,5785	18,19	7,3427E-04
93,89	8670,63	,5785	2,94	1,8718E-02
3,52	10603,23	,5785	20,73	5,7385E-04
,92	13287,19	,5785	43,58	1,1969E-04
1,69	8208,06	,5785	25,81	3,5591E-04
20,07	9701,96	,5785	8,03	3,5759E-03
163,26	9026,22	,5785	2,11	3,1266E-02
6,95	10889,68	,5785	14,38	1,1032E-03
7,98	8362,06	,5785	11,84	1,6496E-03
4,08	8837,94	,5785	16,92	7,9801E-04
10,04	8169,68	,5785	10,57	2,1243E-03

THE WEIGHTED MEAN 4-PI COUNT RATE IS 10011,24 CPM,

THE WTD STANDARD DEVIATION IS 2,1967E+03

THE TOTAL COUNTING TIME WAS 4633,18 MINS

THE TOTAL WT FACTOR IS 2,5785E+07

THE TOTAL NO, OF COUNTS OBSERVED WAS 3,7062E+04

PU-239 LX-RAY AND GAMMA RAY INTENSITIES FOR SOURCE P-5611

THE PHOTON ENERGY IS 59,543 KEV,

OBS,RATE(CPM)	4-PI RATE(CPM)	EFF,	DIST,	G-FACTOR
95,41	40819,00	,6080	8,03	3,8446E-03
94,72	39474,54	,6080	8,03	3,9468E-03
17,84	39963,65	,6080	18,19	7,3427E-04
454,71	39957,11	,6080	2,94	1,8718E-02
13,88	39784,43	,6080	20,73	5,7385E-04
3,42	47000,22	,6080	43,58	1,1969E-04
9,06	41870,70	,6080	25,81	3,5591E-04
87,44	40220,80	,6080	8,03	3,5759E-03
788,57	41485,34	,6080	2,11	3,1206E-02
27,07	40359,62	,6080	14,38	1,1032E-03
40,49	40372,58	,6080	11,84	1,6496E-03
20,24	41718,61	,6080	16,92	7,9801E-04
50,92	39426,48	,6080	10,57	2,1243E-03

THE WEIGHTED MEAN 4-PI COUNT RATE IS 41946,07 CPM,

THE WTD STANDARD DEVIATION IS 2,8465E+03

THE TOTAL COUNTING TIME WAS 4633,18 MINS

THE TOTAL WT FACTOR IS 1,1768E+08

THE TOTAL NO, OF COUNTS OBSERVED WAS 1,8045E+05

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY AFWL (WLBN) Kirtland AFB, NM 87117

13. ABSTRACT (Distribution Limitation Statement No. 2)

A method of absolute counting was used to determine a value of 0.0459 $\pm$ 0.0014 for the ratio of L-X-rays to alpha particles emitted by Pu-239. The relative intensities observed for the $L_\alpha/L_\beta/L_\gamma$ X-ray groups were 1.00/1.23/0.27 respectively and a value of 3.04 $\pm$ 0.57 x 10^{-4} was obtained for the ratio of 51.56-kev gamma rays to alpha particles emitted by Pu-239. The emission rates of alpha particles were measured with a detector made of lithium-drifted silicon, operated at room temperature and at a pressure of 0.001-torr. The emission rates of photons were measured with a detector made of lithium-drifted germanium (Ge(Li)), cooled to a temperature of 77°K. All measurements were recorded with a 400-channel pulse-height analyzer. The efficiency of the Ge(Li) detector for photoelectric interactions was established from a series of measurements of a source of Am-241 with a known activity. The geometric arrangements of the sources and the detectors were varied widely to avoid biased results that may have accrued if all measurements had been made with the geometry fixed. The count rates recorded by the detection apparatus were corrected for the efficiency of the detector and the geometry of the measurement by means of a computer program, to yield the rate of emission of the source for each energy of interest.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Plutonium						
L-X-rays						
X-rays						
Photons						
Alpha particles						
Absolute counting						

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